Production Monitoring of a RTM Automotive Control Arm by means of Fibre Optic Sensors

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Abstract

In this study, a sensor network based on Fibre Bragg Grating (FBG) sensor has been embedded in a carbon fibre reinforced control arm car component, which was produced by Resin Transfer Moulding (RTM) technique. Two main challenges were to be overcome: first, the integration of the sensors lines in the existing RTM mould without modifying it; second, the demoulding of the control arm without damaging the sensors lines. Both tasks were successfully achieved and the process was monitored. The wavelength shifts of the FBGs were observed from the initial production stages, over the resin injection, the complete curing of the resin and the cooling-down prior to demoulding. The sensors proved being sensitive to detecting the resin flow front and afterwards the build up of residual strains induced by the curing shrinkage. The sensors survived after demoulding, and were further used to track the residual strain state of the component in a post-cure process.

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Introduction

Composite materials offer several possibilities of manufacturing and integration of features (e.g. stiffeners) in one and the same production step, which is not feasible with classical construction materials. In fact, complex shapes can be produced in one single production step, thus avoiding assembly to a great extent. Depending on the specifications of the components, different production techniques are used. Amongst them, Resin Transfer Moulding (RTM) is particularly attractive because of its repeatability, short process time, and ability to achieve high fibre volume fraction. This process requires a closed mould, in which the fibre preform is placed before the resin is injected and allowed to cure. A critical step during the process is certainly represented by the resin injection, where the resin flows from one or more inlets towards the outlets and so impregnates the reinforcement fibres. However, during this stage the resin might not completely fill the mould, resulting in harmful dry spots. These dry spots can often be hidden inside the laminate and hence remain undetected. This is not a problem for non-structural components, but since dry spots can significantly reduce mechanical properties of the composite, it will adversely affect the lifetime of structural components. Therefore, it is important to know the exact location of the resin flow front inside the mould for a better understanding and optimization of the injection process [1]. This can be achieved using sensing technology in different ways by integrating a sensor network in the mould or by embedding sensors directly into the composite preform [2]. When integrating sensors into a mould the focus will only be for production monitoring and process optimization [3-5], while embedding them into the preform allows using the sensor network for Structural Health Monitoring (SHM) purposes after production [5-8].
Amongst other sensing technologies, fibre optics can be successfully embedded in composite laminates and be employed as temperature or strain monitoring [9,10], as well as for damage detection via a frequency based approach [11]. Their high pressure and temperature sensitivity allows them to detect sudden pressure increases in the mould, as well as increases of temperature related to the flow of resin over the sensor and the exothermic related to the curing of the resin [12]. What often is omitted in industrial practice is considering the effects of the residual strains induced after manufacturing on the in-operation lifetime of the designed component. These strains can be considerably high [10, 13] especially for complex layups and geometries. A drawback of using fibre optics in RTM processes is its fragility; the sensor needs to survive all steps of the process, of which the demoulding is the most critical. Several fibre optic egress methods have been considered in literature [14] some of them requiring expensive optical mirrors.
In this experimental work, a Fibre Bragg Grating (FBG) sensor network was embedded in an automotive control arm produced by RTM, without modifying neither the mould design, nor the process. As explained later on, an easy and cost-efficient solution for the fibre egress has been adopted. A total of 12 gratings were placed in different layers and at different locations in the carbon fibre preform. During the process, the sensors were able to detect the increase of temperature and pressure, the resin filling the mould and the resin shrinkage after cooling-down. After demoulding, the part has been post-cured in order to increase its mechanical properties. The sensors have undergone a different level of shrinkage depending on their location, in some cases the measured residual-strain level being 0.1%. After manufacturing, the control arm has further been prepared for a modal analysis investigation and its natural frequencies have been measured

via the FBG sensors and compared with the ones resulting from a contactless measurement using a laser Doppler vibrometer; the results were found in good agreement [15].

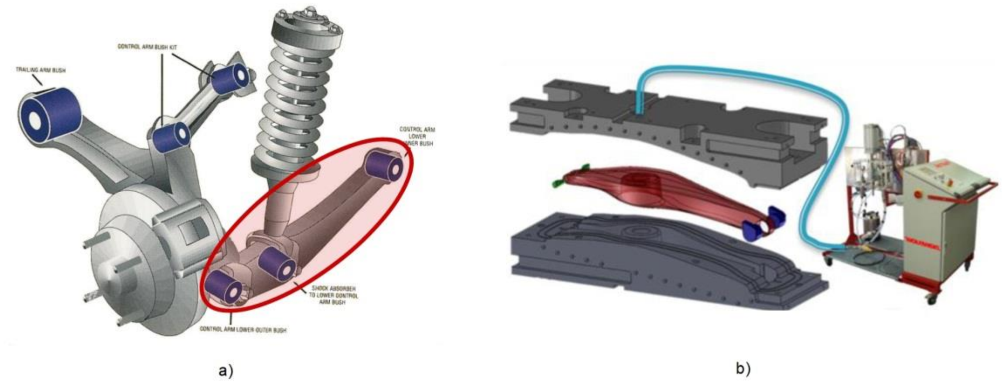

Figure 1: *a) Schematic of the car control arm (source concept motors ltd). b) Schematic of the RTM process.*

Materials & Methods

Preform Preparation

The automotive component was the result of a case study developed as part of the Cornet Project "Design for Manufacturing of Composites" (DeMaCo) (for a public version of the final report see http://slc-lab.be/sites/default/files/DeMaCo%20Public%20report.pdf). Main goal of the project was defining guidelines for composite manufacturers who are willing to start the production of new composite components. A conventional car suspension control arm made of steel was chosen for demonstration purposes and a redesign to a composite sandwich structure produced by RTM was made. For this purpose a mould was designed and manufactured and optimal process parameters were selected. The composite component consisted of a PET foam core reinforced with a carbon fibre/epoxy skin. Two metallic bushings, serving as supports for the suspension assembly, were inserted in the core at its opposite ends. As an initial trial, it was decided to produce a first control arm without embedding any fibre optics. Firstly, the foam core was CNC-machined according to the designed geometry; then the metallic bushings were inserted and fixed in place by two unidirectional (UD) layers of dry carbon fibres running along the whole foam perimeter, as shown in Figure 2b. These layers provided the arm most of the longitudinal stiffness required by the design. Next, a carbon fibre twill layer was draped over the entire core surface as depicted in Figure 2c, thus concluding the preform preparation. The preform was then inserted in the lower-half of the mould – Figure 2d – the mould was closed by the upper-half and sealed. Prior starting the production, the mould and the resin was preheated to 40°C in order to maintain the resin at a constant temperature during the injection. The mould had two ingress lines where the resin was injected at 5 bars, and two vacuum outlets were the resin was sucked out in order to improve its flow into the mould cavities. Once the resin reached the outlets, the process was stopped and the mould cooled-down by means of the same heating system used for the preheating. Finally the mould upper-half was removed and the component demoulded, as represented in Figure 2f.

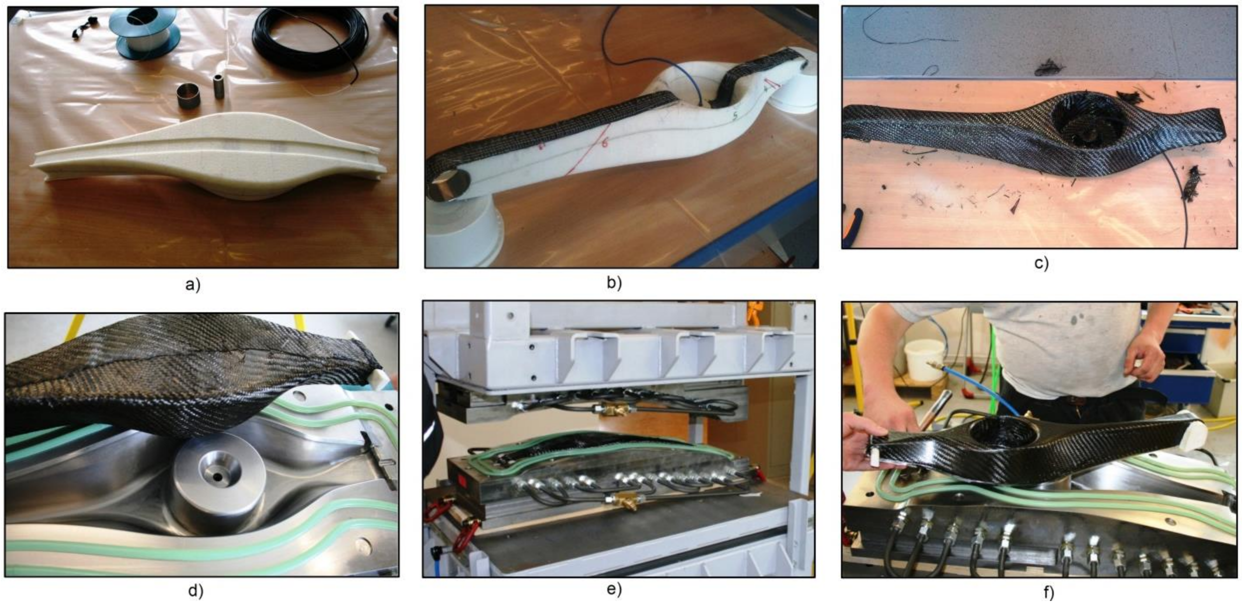

Figure 2: *Overview of the RTM control arm production steps a) machined PET foam core. b) UD reinforcing layers and end-bushings placement c) preform d) preform insertion in the mould e) mould closure f) demoulding after production.*

Sensor Network Placement

After an initial trial, another control arm was manufactured, but in this case a network of 12 fibre Bragg grating sensors (FBGs) was embedded. This, to prove the feasibility of integrating a sensor network in a complex composite component without changing its design, its mould geometry or its production process (RTM). As depicted in Figure 3a-b-c, two 125 µm fibre optics have been embedded in the carbon fibre lay-up of the control arm. Fibre 1 – in green – had 5 sensors, while fibre 2 – in red – had 7; the gratings were equally spaced with 9 cm in between. In Table 1, the location of each sensor on the control arm and its position in the lay-up is reported.

Ch1 – green line	location on the arm	position on the lay-up
1-1	longitudinal bottom	UD/UD
1-2	longitudinal top	UD/UD
1-3	45° side	foam/twill
1-4	45° side	foam/twill
1-5	extra FBG	foam/twill
Ch2 – red line	**location on the arm**	**position on the lay-up**
2-1	longitudinal bottom	UD/UD
2-2	longitudinal bottom	UD/UD
2-3	side FBG	UD/UD
2-4	longitudinal top	UD/UD
2-5	45° side	foam/twill
2-6	45° side	foam/twill
2-7	extra FBG	foam/twill

Table 1: *Position of the FBGs on the control arm and their location in the lay-up.*

A total of 6 gratings have been placed in between the 2nd and the 3rd UD carbon layers strips, of which 5 were intended to capture the bending behaviour of the structure and the remaining one – grating 2-3 was placed at one end of the control arm over the bushing. Other 4 gratings have been placed oriented at 45° between the foam core and the satin twill layer, with the purpose of capturing the torsional behaviour under loading of the structure. The remaining 2 gratings were positioned according to the fibre egress path somewhere close to the spring housing of the control arm and were useful mainly for production monitoring (i.e. resin flow). The two fibre optics were protected with teflon tubing suitably shaped and sealed – as shown in the enlargement of Figure 3a – respectively , in order to facilitate the accommodation of the fibres in the composite and avoid the flux of resin into the tubing.

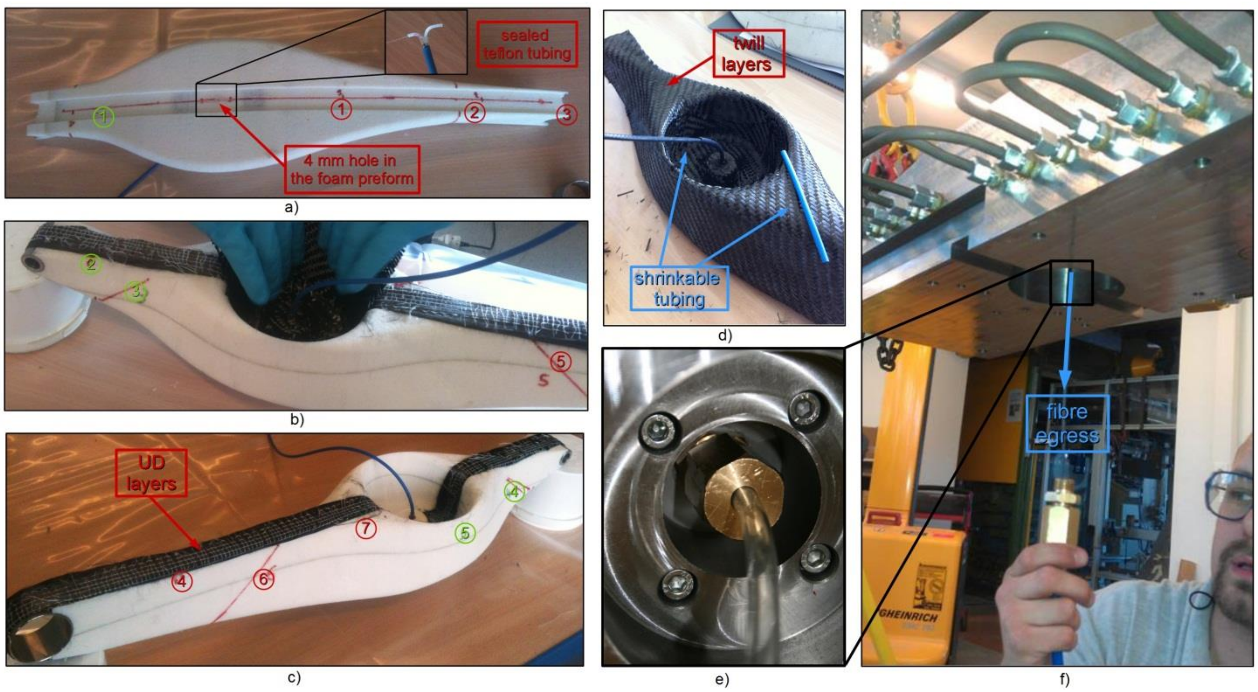

Figure 3: *Overview of the fibre optic embedding. a),b),c) sensor placement, d) preform finalization and detail of the fibre egress protected with a shrinkable tube, e),d) mould vacuum egress where the fibre was slid through and demoulding phase with the disconnection of the egress.*

The two shaped-tubes were joined together in a larger tubing, which was slid through a hole machined in the PET foam and egressed the control arm on the spring housing, as highlighted in Figure 3d. Once the preform was prepared and the fibre-egress reinforced with some stiffer tubing, the whole system was housed in the mould and the fibre was slit through the vacuum outlet, in order to be able to access it and monitor the process.

Demoulding

In order to be able to demould the control arm without harming the fibre optics, a sacrificial shrinkable tube was put over the fibre, which could slip-out from the fibre once the vacuum outlet tube (filled with resin) was removed. To facilitate the sliding some grease was applied between the fibre optic tubing and the sacrificial tube. After removing the vacuum outlet and allowing enough time for cool-down, the control arm was easily removed.

Experimental Results

Cure monitoring

The process was monitored starting when the mould was closed and ending once the mould was cooled down to room temperature. Each wavelength peak was acquired using a centre-of-gravity (COG) algorithm and was recorder continuously during the whole duration of the production process, which was approx. 6h. In addition, the full fibre spectra were acquired at relevant time-steps during the process, namely: the spectra prior to embedding, once the resin was injected into the mould and reached all the sensors, once the resin cured, once the upper-half of the mould was removed and after complete cool-down prior to the demoulding. The scanner used during the acquisition was the FBG-Scan 804 from FBGS® with a 1510-1590 nm wavelength range and a ±1 pm wavelength resolution. In Figure 4 the resulting signals from the cure monitoring are represented. The initial wavelength shift clearly show the pre-heating applied to the mould during the 1st h of the process.

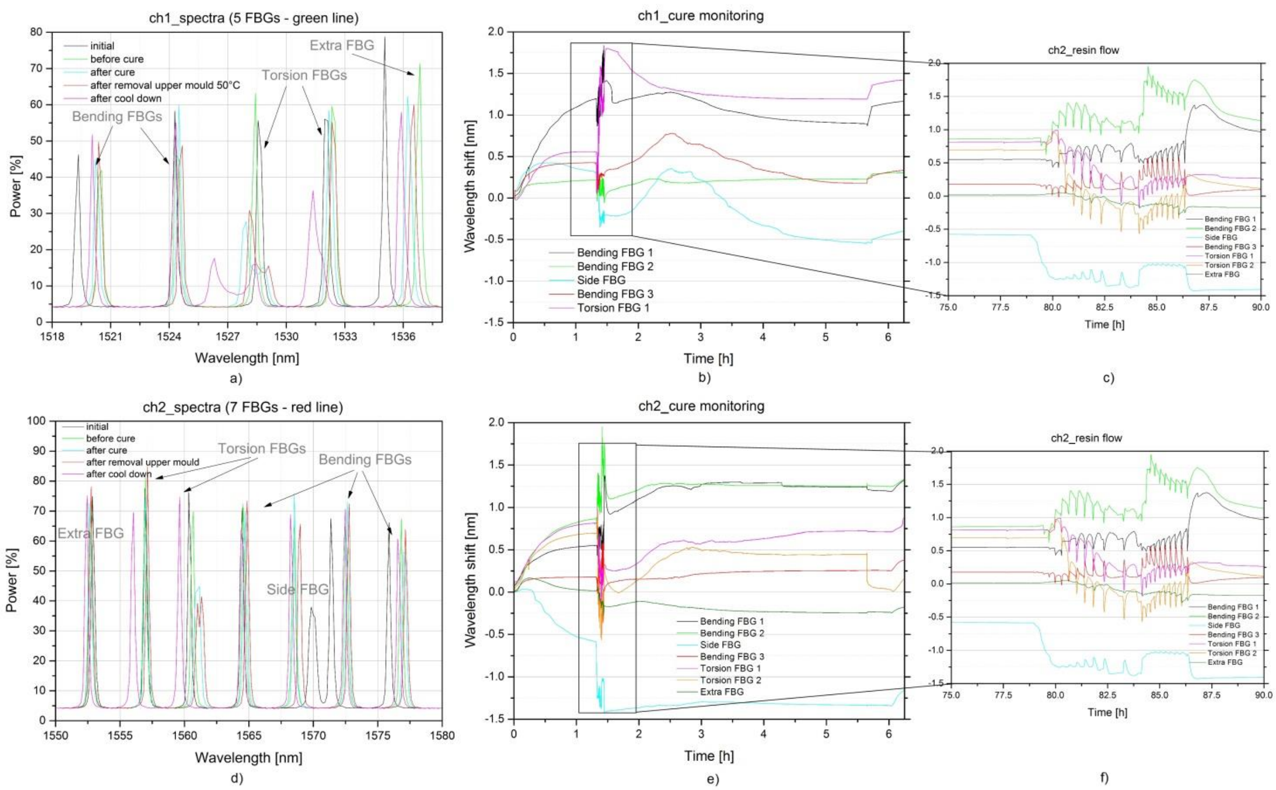

Figure 4: *Spectra a), e) and wavelength shift b), f) of the 2 fibre optic lines during the RTM process. c) and g) are highlighting the resin injection phase.*

At the same time, also the pressure used to seal the mould is influencing the measurements. About 1 h after starting the process, the resin was injected at an initial pressure of 5 bars and when it reached the sensors, a sudden wavelengths jump was noticed. This is a combined result of the increase of temperature (the resin was injected at 40°C) and pressure and of a possible grating repositioning induced by the resin flow. Paying attention to the enlargements c) and g) of Figure 4, one can notice that the whole injection lasted not more than 15 minutes in which the strokes of the resin piston pump could be recognized. Afterwards, the wavelength shifts kept reasonably constant until approx. 5.5 h when the part was cooled down before demoulding. Analysing the spectra before curing (green line – Figure 4a-e) and after cooling down (magenta line – Figure 4a-e), one can deduce that the resin curing is in general decreasing the wavelength peaks. This is especially the case for the “Torsional FBGs” or the “Extra FBGs” which are embedded in direct contact with the PET foam; in fact, in these surroundings the resin uptake is expected to be higher. On the other hand the FBGs embedded between two UD layers reveal a lower shrinkage thanks to the supporting fibre stiffness. In general the “Torsional FBGs” show peak distortions, as a result of transversal pressure acting on the grating.

Post-cure monitoring

After the delicate demoulding operation, the control arm was post-cured in an oven for 48 h at 50°C; details of the temperature cycle can be found in Figure 5a. The wavelengths shift was monitored continuously during the post-cure and spectra were acquired before, during and after the temperature cycle.

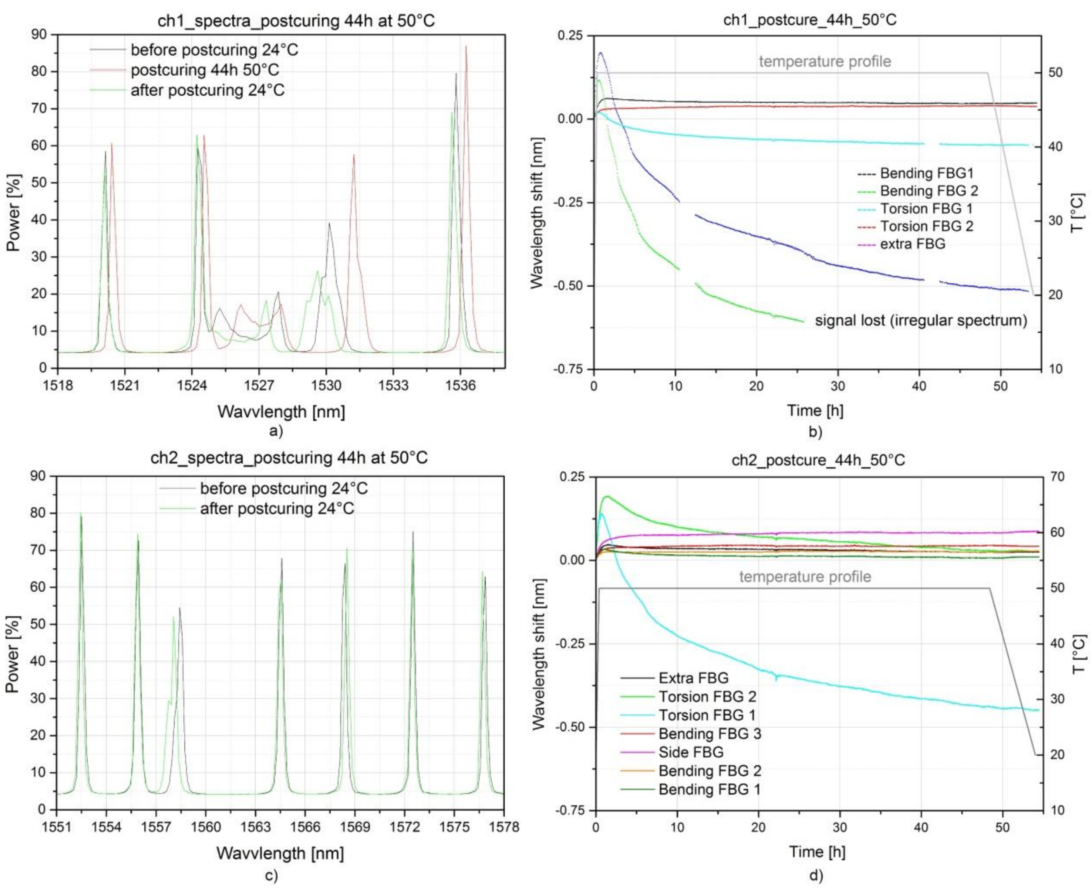

Figure 5: *a), c) Spectra and b), d) wavelength shift of the 2 fibre optic lines during post-curing.*

In this case, the overall wavelength shift is less important with respect to the one recorded during curing; still a peak is noticed at the early stage of the post-cure, when the temperature reaches 50 °C. This is the effect of a strain relaxation inside the composite, which is directly connected with the residual amount of resin polymerization. The wavelength shift scatter observed between the different sensors might be connected to the different amount of polymerization to which the resin was subjected during the RTM process (i.e. different thicknesses, non-homogeneous temperatures). In this sense the post-curing process allows the component to have chemical and physical properties more homogeneous [16]. For completeness the values of the wavelength before curing, after curing and after post-curing are reported in Table 2. It can be noticed that the sensors subjected to higher residual strain level are the "torsional sensors" (in contact directly with the PET foam) and the "side FBG" (placed over the bushing), which present also peak distortion.

Ch1	**initial**	**after cure**		**before post-cure**		**after post-cure**	
	[nm]	**[nm]**	**ε [%]**	**[nm]**	**ε [%]**	**[nm]**	**ε [%]**
1-1	1519.346	1520.056	0.0592	1520.131	0.0654	1520.085	0.0616
1-2	1524.298	1524.345	0.0039	1524.255	-0.0036	1524.211	-0.0073
1-3	1528.566	1528.357	-0.0174	1527.860	-0.0588	1527.327	-0.1032
1-4	1532.050	1531.418	-0.0527	1530.139	-0.1592	1529.612	-0.2031
1-5	1535.048	1535.910	0.0718	1535.811	0.0635	1535.614	0.0472

Ch2	**initial**	**after cure**		**before post-cure**		**after post-cure**	
	[nm]	**[nm]**	**ε [%]**	**[nm]**	**ε [%]**	**[nm]**	**ε [%]**
2-1	1552.867	1552.440	-0.0356	1552.502	-0.0304	1552.445	-0.0351
2-2	1556.926	1556.010	-0.0763	1555.940	-0.0821	1555.887	-0.0866
2-3	1560.370	1569.624	0.7711	1558.430	-0.1616	1558.066	-0.1920
2-4	1564.486	1564.404	-0.0068	1564.588	0.0085	1564.492	0.0005
2-5	1569.925	1568.237	-0.1406	1568.529	-0.1163	1568.356	-0.1307
2-6	1571.380	1572.478	0.0915	1572.506	0.0938	1572.472	0.0910
2-7	1575.878	1576.625	0.0622	1576.834	0.0796	1576.693	0.0679

Table 2: *FBGs central wavelength residual strains at different stages during the process.*

Conclusion

This work proved the feasibility of successfully embed a fibre optic sensor network based on FBGs in a carbon fibre reinforced epoxy automotive component made by a RTM production process. This has been achieved without bringing any changes to the mould or to the suspension control arm design. The production process was monitored and the FBG sensors have proved being capable of detecting the increase of temperature and of pressure inside the mould and the resin filling. Furthermore, a method which allowed to safely demould the control arm without harming the fibre optics has been presented.

After production the sensor network was used to perform a dynamic analysis in order to detect the vibrational modes of the control arm and compare them with another reference modal analysis technique. The results are disclosed in the work of Lamberti et al. [15].

Acknowledgements

The research leading to these results has received funding from the Flemish Agency for Innovation by Science and Technology (IWT) – through the program for Strategic Basic Research (SBO) under grant agreement n° 120024 (Self Sensing Composites). The author gratefully acknowledges also the significant support of SLC – Sirris Leuven-Gent Composites Application Lab for providing the manufacturing facilities and of the spin-off company of Ghent University – Com&Sens – which provided significant expertise for the sensor network embedding.

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