FIBRE OPTICAL TEMPERATURE SENSOR FOR DISTRIBUTED SENSING IN COMPOSITE MOULDS

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ABSTRACT

The temperature is the driving parameter in thermoset resin curing processes during composite manufacturing. In larger parts the temperature distribution can be uneven due to heat conduction effects or exothermic resin reaction. For that reason, composite moulds for manufacturing of wind turbine rotor blades are equipped with a growing number of mould-integrated heating circuits. In order to allow independent temperature control, each circuit has to be equipped with at least one temperature sensor.

Until today, this is realised by integrating electrical single-point sensors into the composite mould. Their major drawback is the high application effort during mould manufacturing. Therefore, we want to develop a multi-point temperature sensor which can be applied in large composite moulds. This sensor has to be robust and flexible enough to withstand the lamination process.

We developed a fibre optical temperature sensor based on quasi-distributed sensing with fibre Bragg gratings (FBG). The novelty is the carbon fibre reinforced plastic (CFRP) tube that encapsulates the FBGs. We performed sensor calibrations to determine the sensor sensitivity with bare FBGs and with FBGs in CFRP tube. At last, we integrated a calibrated multi-point fibre optical temperature sensor in an electrically heated composite mould to monitor temperature distribution during composite manufacturing.

This paper reports about the new sensor design, its mechanical properties and temperature sensitivity, and the application in a CFRP mould. The design we found is adequate for distributed temperature measurements in composite moulds. The characteristic curve of the sensor is linear in the investigated temperature regime and shows small hysteresis. The proposed sensor provides an opportunity to increase the number of temperature measurement points in composite moulds.

We see the potential to reduce mould manufacturing costs by raising the sensor density. This allows more precise temperature monitoring which can be used for optimised process control by composite manufacturers.

1 INTRODUCTION

In larger parts, with varying laminate thickness, the temperature distribution can be uneven due to heat conduction effects or exothermic resin reaction. This can lead to prolonged curing cycles, induced strain or in the worst case to incomplete curing. For this reason composite moulds for manufacturing of wind energy rotor blades are equipped with a growing number of mould-integrated, independent heating circuits (up to 80 circuits per mould). In order to allow independent temperature control, each circuit has to be equipped with at least one temperature sensor.

Nowadays, this is realised by integrating electrical single-point temperature sensors such as thermocouples into the composite mould. This has the major drawback that each single temperature sensor has to be installed and has to be guided out from the laminate. This leads to a high application effort during production and a high cabling effort during installation with all the drawback of labour costs and material costs.

Therefore, we want to develop a multi-point temperature sensor which can be applied in large composite moulds. This sensor has to be small, robust and flexible enough to withstand the composite laminate integration, and it has to withstand the cyclic thermal loads during application. Fibre optical sensors are a promising sensing technology but typical sensor structures tend to show unfavourable mechanical properties which might cause sensor loss during industrial application in composite laminates.

We developed a fibre optical temperature sensor based on distributed sensing with fibre Bragg gratings (FBG) with an optimised sensor structure. It meets the requirements for composite laminate integration which is given by wind energy rotor blade manufacturers. We performed sensor calibrations to determine the measurement sensitivity with bare FBGs, with FBGs housed in the sensor structure. The calibrations were performed in a thermal chamber between 20 °C to 140 °C. At last, we integrated a calibrated multi-point fibre optical temperature sensor together with heating circuits in a composite mould to monitor temperature distribution during composite manufacturing.

The paper reports about the new design of a fibre optical temperature sensor and the mechanical properties of the sensor structure. This is followed by the calibration of the sensor and the application in a CFRP mould.

2 MATERIALS AND METHODS

2.1 Sensor design and mechanical characterisation

In this work we used FBGs as temperature sensors. An FBG is a periodic perturbation of the effective refractive index n_{eff} of an optical fibre. When broadband light is guided through the optical fibre the FBG reflects a characteristic narrow reflection peak with centre wavelength λ. FBGs are sensitive to temperature T and strain ε. The sensor response to a change of temperature and of strain can be described by eq. 1 [1]. Here, the initial state is given by index 0.

$$\Delta\lambda/\lambda_0 = (1 - p) \cdot \varepsilon + (\alpha + 1/n_{eff,0} \cdot dn_{eff,0}/dT) \cdot \Delta T \qquad (1)$$

With the photo-elastic coefficient $p = 0.22$ [1], thermal expansion coefficient of the silica fibre $\alpha = 0.55 \cdot 10^{-6}$ [2] and the thermo-optic coefficient $1/n_{eff,0} \cdot dn_{eff,0}/dT = 8.6 \cdot 10^{-6}$ for Germanium-doped silica fibres [2]. Under the assumption that the FBG is only subject to temperature changes and no mechanical strain, the resulting wavelength shift can be described by eq. 2.

$$\Delta\lambda/\Delta T = (\alpha + 1/n_{eff,0} \cdot dn_{eff,0}/dT) \cdot \lambda_0 \qquad (2)$$

In order to realise the assumption of no mechanical strain, FBG sensors are typically placed inside a tube. Typical tube materials are glass and metal [3]. All axial strain on the FBG is decoupled by attaching the fibre to the tube, e. g. by gluing. Contamination of the sensor can be prevented by sealing the other end of the tube.

When integrating fibre optical temperature sensors in composite laminates, glass and metal tubes have drawbacks regarding their mechanical properties. Glass tubes are elastic but tend to be brittle. This prevents the application in an industrial environment. Metal tubes in contrast are ductile but exhibit higher stiffness which limits the application in curved structures. During sensor application, excessive loading of the sensor structure might occur and sensor loss due to cracking in the case of glass or due to kinking in the case of metal might occur. A more gradual failing of the sensor structure is favourable.

Therefore, we designed a carbon fibre reinforced plastic (CFRP) tube with favourable mechanical properties. The requirements for the new tube were high radial stiffness to withstand rough handling, while being flexible at the same time to allow free sensor application, e. g. in mould manufacturing for wind turbine blades. With this new design we combined the upsides of glass and metal tubes while reducing the respective downsides. The tube was produced by Fraunhofer IPT, Germany, in a pull-winding process in which a reinforcement C-fibre yarn (1K Toho Tenax HT40) was pulled through an epoxy resin bath (Hexion H235/L235) and subsequently wound on a polyimide-coated glass tube with 510 µm outer diameter (OD). A 135µm thin non-overlapping layer of carbon fibre was applied at a winding angle of 30°. Figure 1 shows two microscopy cross sections of the sensor tube. The produced tube has a 400 µm inner diameter (ID) and a 780 µm OD.

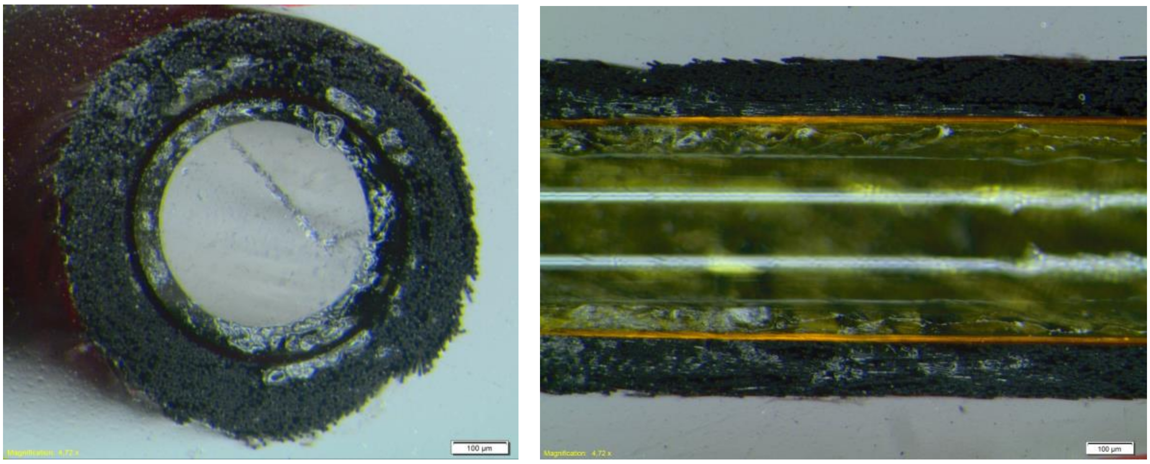

Figure 1: Microscopy of radial (left) and axial (right) cross section of fibre reinforced sensor tube with a core of glass tube and polyimide coating.

The mechanical properties of the CFRP tube were investigated in a bending and a compression test at ambient temperature. In both experiments the CFRP tube was benchmarked against a glass tube with ID 400 µm / OD 510 µm and against a steel tube with ID 345 µm / OD 600 µm. In each experiment, five to seven specimens were tested.

The bending test was performed in a 3-point bending setup of a TA instruments Q800 dynamic mechanic analysis device (DMA). The 30 mm long specimen was placed centrally on the 20 mm spaced supports and was pre-loaded at 0.002 N. The bending was performed at a constant force rate of 0.5 N/min until a deformation of 25 mm was reached.

The radial compression test was performed in an Anton - Paar MCR 302 rheometer by using its load cell and its vertically displaceable shaft as a compression test machine. The load cell has a load capacity of up to 50 N and a normal force resolution of 0.5 mN according to the data sheet. In this test setup the 30 mm long specimen was placed horizontally on a rigid, milled aluminium rheometer dish. The load was applied radially on the specimen by driving the flat head of the cylindrical rheometer shaft transverse to the tube axis onto the specimen. The head had a 10 mm diameter and the specimen was pre-loaded with 0.4 N by clamping it between the dish and the head. During the test the load was increased linearly between 0.4 N and 45 N and the resulting displacement was recorded.

2.2 Sensor calibration and application

We performed the calibration by exposing the sensors to a temperature cycle while recording their response at the same time. Both measurands were then correlated and an equation for the sensitivity S was fitted which describes the right side of eq. 2.

$$\Delta\lambda / \Delta T = S \tag{3}$$

We used this approach because neither exact values of the thermal expansion coefficient nor the thermo-optic coefficient of the applied optical fibre were available. Secondly, the simplified eq. 2 does not account for potential mechanical interaction between FBG and the surrounding, e. g. coating expansion [4] or friction that might occur between sensor and tube wall.

In our experiments we compared the sensor response of bare FBGs and of FBGs housed in CFRP tube under thermal loading, in order to determine if the housing has a noticeable effect. Both specimen types: bare FGs and FGs housed in CFRP tube, were placed in a thermal chamber, where the temperature was cycled three times between 20 °C - 140 °C° with isothermal steps of 1 h every 20 °C. This was done to establish stable temperatures for accurate correlation between wavelength and temperature. At last we demonstrated the applicability of the new sensors in CFRP laminates. Therefore, we applied calibrated distributed temperature sensors in a composite mould and monitored the mould temperature.

In our experiments we used femtosecond laser FBGs with a central wavelength of around $\lambda = 1550$ nm written in 155 µm diameter polyimide-coated SM1250 silica single-mode fibres from Fibercore Ltd. The FBGs were interrogated with a spectrometer-based fos4Test nSens device from fos4X GmbH. Reference temperature measurements were performed with type K thermocouples which were interrogated with a TC - 08 device from Pico Technology Ltd. The sampling rate for both devices was set to 1 Hz.

The measurement setup for the investigation on the bare FBGs consisted of two vertically installed FBGs and one reference thermocouple in close proximity.

The measurement setup for the investigation on the FBGs housed in CFRP tube consisted of three distributed temperature sensors (Figure 2) and two reference thermocouples which were installed horizontally in the thermal chamber. Each distributed temperature sensor consisted of three FBGs written in one optical fibre which was inserted in a straight 180 mm long CFRP tube. The sensors were fixed inside the tube by gluing the optical fibre to the tube at the ingress position. In order to prevent tube contamination the end of the tube was sealed with glue. Since the FBGs were loose inside the tube a certain interaction with the surrounding wall can be expected. This can alter the sensor response especially during temperature cycles where thermal expansion of the tube might induce strain in the FBGs.

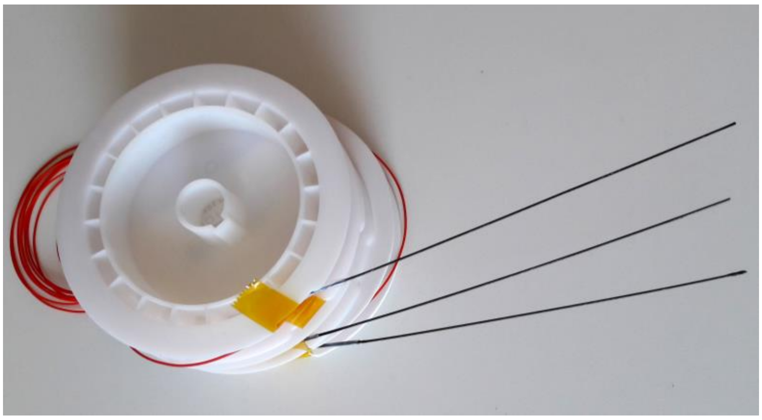

Figure 2: Distributed fibre optic temperature sensors made from CFRP tube.

At last we integrated the previously calibrated distributed temperature sensors into the laminate of a CFRP mould (Figure 3) built by Qpoint GmbH, Germany. A type T thermocouple was positioned next to the fibre optic sensors as reference. For ease of handling the sensors were positioned on a thin fleece ply. The ply does not interfere with the sensor because strain transfer between FBG and ply is decoupled by the CFRP tube. In addition to that the sensors, the CFRP mould had been equipped with integrated electrical heating circuits for mould temperature control. The mould was then heated to several isothermal temperatures between 30 °C and 140 °C and the temperature inside the laminate was monitored by the optical sensors.

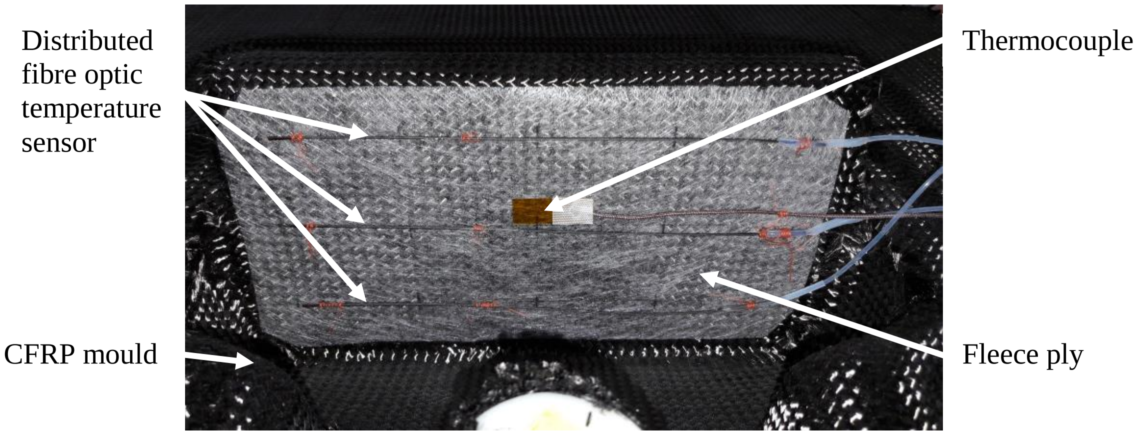

Figure 3: Integration of three distributed fibre optic temperature sensors made from CFRP tube and additional reference temperature sensor during CFRP lamination process. The sensors are fixed on a thin ply for ease of handling.

3 RESULTS AND DISCUSSION

3.1 Sensor design and mechanical characterisation

The 3-point bending test results are shown in Figure 4. The graph shows the measured normal force over the displacement of glass, CFRP and steel tube specimens. Five specimens of each material were tested. It can be seen that all specimens show a linear elastic force increase during initial displacement. In this region the effect of the reinforcement on the tube stiffness is visible since the CFRP tube is roughly four times stiffer than the glass tube. In comparison the steel tube is roughly three times stiffer than the CFRP tube. With progressing bending the CFRP and the steel specimens start to deform plastically. This leads to a gradual degradation of the stiffness. The glass specimens instead show no signs of degradation until they fail suddenly. We used a stiffness change below 0.1 N/mm as a failure criterion. Data points below that value are not plotted. After full displacement the glass specimens were broken into two pieces, the CFRP specimens were deformed with their glass core apparently fractured, and the steel specimens were plastically deformed. This experiment showed that CFRP tubes exhibit lower stiffness than the tested steel tubes and apparently fail more gradually than glass tubes. In order to further lower the stiffness of the CFRP tubes the winding angle from currently 20 ° has to be raised.

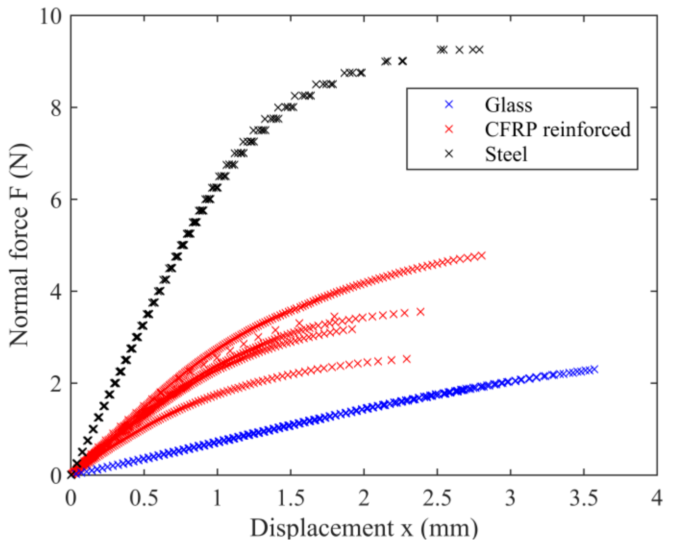

Figure 4: DMA 3-point bending test results of five glass (blue), CFRP reinforced glass (red) and steel (black) specimens.

The compression test results are shown in Figure 5. The graph shows the mean normal force over the displacement of five to seven glass, CFRP and steel specimens. All three materials behave similar and the normal force increases exponentially with increasing displacement. Four out of seven glass specimens failed prematurely. These specimens with preliminary failure are not shown in the graph. In terms of radial stiffness and fail safeness it was evident that the CFRP tube is superior to the glass tube. Due to force restrictions of the rheometer the measurement was stopped at 45 N. Until that limit the test results suggest that the radial stiffness of the CFRP tube was comparable to the stiffness of the steel tube. In summary, the CFRP tube showed favourable mechanical behaviour to other common sensor tubes made of glass or steel. Further, the test results showed that the CFRP tube combines the radial stiffness of the steel tube with the flexibility of the glass tube.

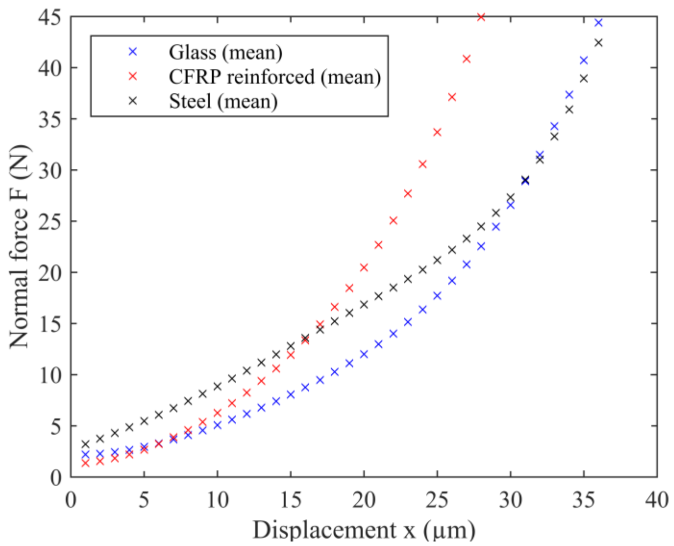

Figure 5: Glass (blue), CFRP reinforced glass (red) and steel (black) tubes under radial compression load measured in a rheometer. Each curve represents the mean curve out of five measurements.

3.2 Sensor calibration and application

The response of a bare FBG during one heating cycle (red) and one cooling cycle (blue) is presented in Figure 6. The plot shows the correlation of the wavelength shift of the FBG and the corresponding temperature shift acquired with a thermocouple. It can be seen that correlation follows a linear trend in the temperature regime between 20 °C and 140 °C. This linear trend can be described with eq. 3 and a sensitivity constant given in Table 1. The bare FBG shows negligible hysteresis between heating and cooling. This lead to almost identical sensor sensitivity during heating and cooling.

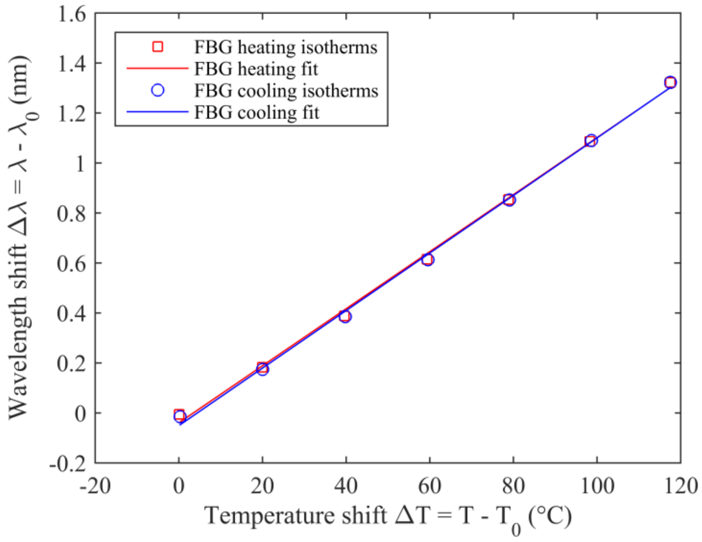

Figure 6: Correlation of wavelength shift and the respective temperature of one bare FBG during one heating and one cooling cycle between 20 °C and 140 °C with isothermal plateaus every 20 °C. The data depicted is the FBG response after temperature equalisation at every plateau. Additionally, the respective linear fit is shown.

Sensitivity $\Delta\lambda/\Delta T$		Heating	Cooling
S_1	[pm/K]	11.4	11.5

Table 1: Sensitivity of a bare FBG during heating to 140 °C and cooling to 20 °C.

An exemplary response of a distributed fibre optic temperature sensor under cyclic thermal loading is shown in Figure 7. Depicted is the wavelength shift of three FBGs during one temperature cycle between 20 °C and 140 °C correlated with the temperature data obtained from a thermocouple. Similar to the bare FBG behaviour we can observe a linear trend of the correlation in the temperature regime between 20 °C and 140 °C which can be described with eq. 3. Again, almost no hysteresis is visible between heating and cooling. All three FBGs show a very similar linear behaviour which is evident by the sensitivities given in Table 2. This suggests that the CFRP tube had no negative effect on the sensor response in a non-bent sensor application.

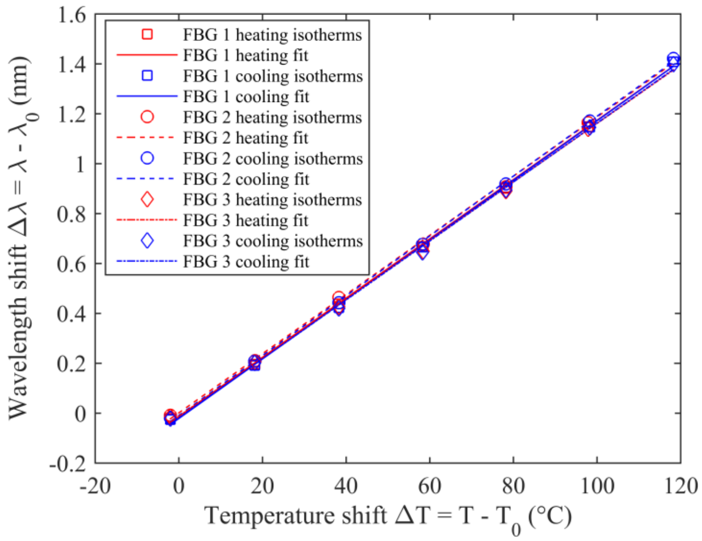

Figure 7: Correlation of the wavelength shifts and of the respective temperature of three FBGs housed in a CFRP tube during one heating and one cooling cycle between 20 °C and 140 °C with isothermal plateaus every 20 °C. The data depicted is the FBG response after temperature equalisation at every plateau. Additionally, the respective linear fits are shown.

Sensitivity $\Delta\lambda/\Delta T$		Heating	Cooling
S_1	[pm/K]	11.9	12.0
S_2	[pm/K]	11.9	12.0
S_2	[pm/K]	11.8	11.8

Table 2: Sensitivity of the distributed temperature sensors during heating to 140 °C and cooling to 20 °C.

Figure 8 shows a representative result of the measured temperature as a function of time of one distributed optical sensor with three single FBGs housed in a CFRP tube. The measured temperature curve represents the mould temperature generated by the integrated electrical heating system. The temperature curves were calculated with eq. 3 with the initial wavelengths λ_0, the initial temperature T_0, the respective wavelength shifts $\Delta\lambda$ experienced by the FBGs and the sensitivities determined during the calibration in the thermal chamber (see Table 2). We observed that each FBG showed a very similar behaviour which indicated, that the sensors response is not negatively influenced by the lamination process. The sensors revealed that the temperature over-shoots slightly at the beginning of each isotherm which is followed by a sawtooth temperature profile of the temperature control.

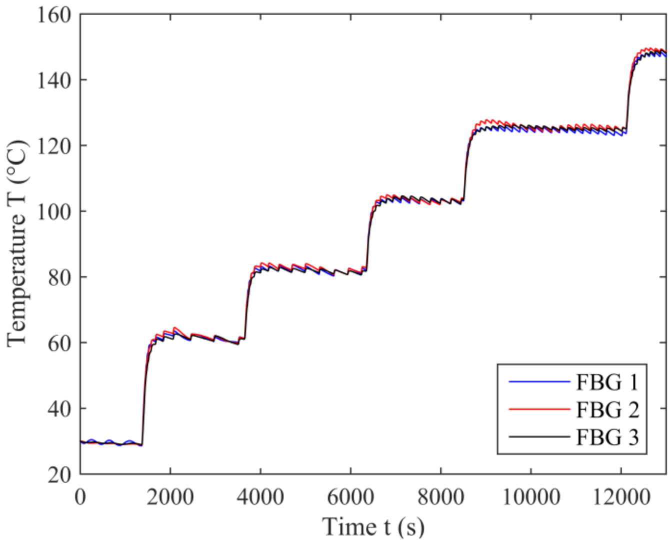

Figure 8: Distributed temperature sensing in a CFRP mould with integrated fibre optic sensors during temperature ramp up with mould-integrated electrical heating circuit. Shown are the values of three FBGs written-in one optical fibre which is housed in a CFRP tube. During the isotherms the heating controller activity is observable by its characteristic sawtooth temperature modulation.

4 CONCLUSION

We developed a fibre optic temperature sensor based on a CFRP reinforced sensor tube. The CFRP sensor structure addresses the need for a flexible, yet radially stiff sensor tube for laminate integration in rough environments. Straight fibre optic temperature sensors made from the CFRP tube show linear behaviour between 20 °C and 140 °C with a sensitivity of 12 pm/K. We integrated the sensors in a CFRP mould and demonstrated that fibre optical CFRP tube temperature sensors are suitable for distributed temperature sensing in composite structures.

For the application in larger, curved structures such as wind turbine blade moulds we anticipate that sensor curvature might affect the sensor response, e. g. stronger hysteresis. In order to meet accuracy requirements this has to be investigated further.

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