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# MONITORING OF THERMOSET COMPOSITES CURING BY STRUCTURAL HEALTH MONITORING (SHM) SENSORS

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## 1 Introduction

Composites parts number is growing in the aeronautic sector in reason of their high mechanical properties and their opportunity of complex shapes designing. However, the properties of these materials are highly dependent on their manufacturing conditions, and so a better knowledge of the elaboration process could permit an enhancement of the material quality. For this purpose, different process monitoring can be proposed, as a Structural Health Monitoring (SHM) sensors-based instrumentation. Indeed, such methods allow monitoring thermomechanical stresses to which the structure is subjected during its manufacturing step as well as its lifecycle.

For thermoset composite parts, the integration of SHM sensors can be used to monitor the matrix curing [1-3], that has a direct impact on the matrix viscoelastic properties.

Thus, this article focuses on the embedment of SHM sensors as Fibre Bragg Grating (FBG) or strain Quantum Resistive Sensor (sQRS) into the core of a thermoset composite in order to estimate its curing degree from measured strains during the manufacturing process.

## 2 Monitoring of manufacturing process

### 2.1 Manufacturing process

This article interests in the manufacturing of unidirectional thermoset laminates by Vacuum-Bag-Only (VBO) process: the laminate lay-up is placed under a vacuum-bag that permits to apply a compaction pressure around 1 bar by vacuum drawing. Moreover, to ease the instrumentation, the thermal cycle is applied by a heating plate, and not by an oven.

Different kinds of unidirectional carbon fibres / epoxy matrix with and without thermoplastic nodules are

considered. It can be underlined that these prepregs were not designed for out-of-autoclave applications.

### 2.2 Instrumentation set-up

The VBO process offers the opportunity to be easily instrumented. In this way, the monitoring set-up is composed by one SHM sensor and by two thermocouples: one close to the SHM sensor to allow thermal compensation and one on the top of the laminate to control the temperature gradient through the thickness. The SHM sensor is positioned at half-thickness and in the centre of the laminate. Moreover, it is oriented perpendicular to the fibres, to monitor the resin phenomena.

Both selected sensors (FBG and sQRS) are sensitive to temperature and strains according to the equation (1). With  $\lambda$  the wavelength or the resistance, for respectively a FBG or a sQRS.  $K_T$  and  $K_\varepsilon$  are the coefficients of sensitivity to temperature and to strains.

$$\Delta\lambda = K_T \cdot \Delta T + K_\varepsilon \cdot \varepsilon \quad (1)$$

An acquisition of sensors signals is made every five seconds throughout the curing cycle

### 2.3 Curing kinetic law

In order to correctly interpret the strains measured by SHM sensors, it is required to rely on the matrix curing kinetic law. In this paper, the kinetic law is considered as an analytic model of Kamal-Sourour (2), with  $k_1$  and  $k_2$  that follow an Arrhenius law. The parameters of the model were identified from Differential Scanning Calorimetry (DSC) tests data.

$$\frac{d\alpha}{dt} = (k_1 + k_2 \alpha^m)(1 - \alpha)^n \quad (2)$$

### 3 Results and discussion

#### 3.1 Strains and temperature monitoring

The sensors data acquisition throughout the manufacturing cycle permits to get the strains and temperature evolutions during the composite curing. The figure 1 shows these evolutions in the case of an unidirectional laminate  $[0]_8$  with a FBG at the centre and oriented perpendicular to the fibres. The applied thermal cycle is composed by a 1K/min heating rate, a 3h plateau at 180°C and a free cooling rate. In this case, the strains are measured by a FBG after thermal compensation according to the equation (1). According to the curing kinetic model, the cross-linking phenomenon takes place from around 100°C until the end of the temperature plateau.

Different phases can be identified from strains evolution. During the heating step, strains do not change very much. Indeed before the matrix curing, FBG is not connected to the laminate, and so can not measure composite strains. Moreover, a strains drop appears at the temperature plateau, that can be caused by the matrix curing. Finally, during the cooling phase, the FBG measures only the thermal shrinkage of the laminate.

#### 3.2 Chemical shrinkage and curing degree

From the monitoring data and the kinetic model, it is possible to study the link between the chemical shrinkage and the curing degree. To better understand this connection, the evolution of the chemical shrinkage in function of the curing degree has been studied for multiple cycle conditions (different heating rates, plateau temperatures and durations). The Figure 2 shows this study for thermal cycles with different plateau temperatures. As expected the more cured the matrix, the greater the chemical shrinkage. However, these results underline that the link between the chemical shrinkage and the curing degree is not linear, and more particularly that the shrinkage takes place above a limit value of around 0.55.

### 4 Conclusion and perspectives

This study highlights the opportunity to monitor the composites curing thanks to a SHM set-up. It investigates more particularly the possibility of estimating an order of magnitude of curing degree

directly from strains monitoring. Further works on the matrix cross-linking paths have to be done, to improve the curing degree predictions from aq SHM set-up.

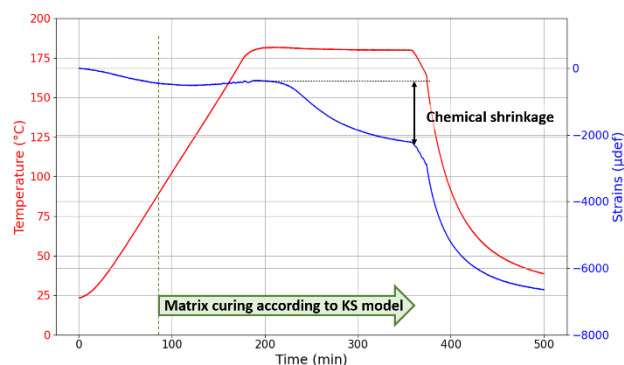


Fig. 1. Strains and temperature monitoring during curing cycle

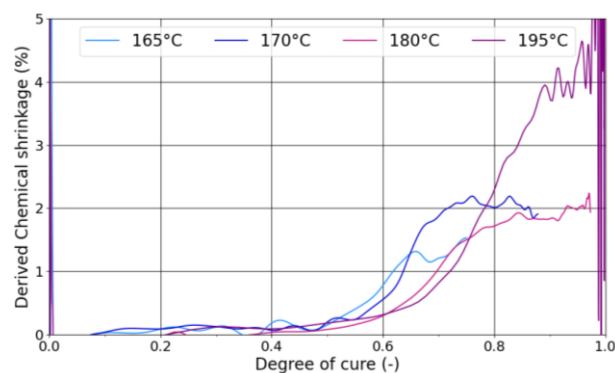


Fig. 2. Evolution of chemical shrinkages in function of the matrix cure degree at different plateau temperatures

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