SIMULATION AND TESTING OF STRUCTURAL COMPOSITE MATERIALS EXPOSED TO FIRE DEGRADATION

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Abstract
On this paper, a sort of flat laminates with several thicknesses and cross ply lay-up were experimentally tested under fire condition. FBG sensors, both for temperature and strain, were embedded at four different depths in order to monitor the structure. Matrix degradation and strains due to thermal and residual stresses will be compared to a Finite Element Model which will allow implementing the material property changes to validate all the physical phenomena involved.

1. Introduction

Composite materials are designed to provide optimal properties for many structural applications. One barrier to the implementation of composites, especially in the aerospace industry, is their inherent combustibility and the associated risk from fire.

Although most composites are flammable, they have long been known to show a better tolerance to thermal insult than expected. Thermal resistance properties are due to a combination of low thermal conductivity, good structural integrity and significantly, the endothermic decomposition of the matrix, which slows down the heat transmission through the laminate. The phenomena that take place on polymeric matrix composites exposed to a fire test are complex and difficult to measure, mainly because the property changes, both thermal and mechanical, associated to the material decomposition.

Applications of composite materials structures are not limited for the risk of fire on attached systems, although its influence on the matrix of polymer materials is obvious. Therefore, in order to get a correct sizing and a better structural optimization, it is necessary to know the phenomena that take place on the matrix degradation and its influence on thermal and mechanical properties. Even though current certification standards just verify the global properties of the structure subjected to fire, understanding the loads and heat transmission within the structure is crucial. Therefore, property changes through the laminate thickness involve measuring both temperature and strain over different plies inside the laminate.

In order to obtain information for validating the model, conventional temperature or strain sensors can't be used, since they are highly invasive and measures would be conditioned by the presence of such sensors. On the other hand, with temperature or strain sensors based on surface techniques such as infrared or thermography it is not possible to know strain fields or the thermal diffusion into the material, so neither can obtain information to verify the physics of the problem. Thus, in order to obtain information from the strain field and temperature distribution within the material, fiber optic sensors based on Bragg diffraction law are going to be used. Fiber Bragg Grating (FBG) sensors, in addition to the inherent properties of fiber optic sensors (low weight, immunity to electromagnetic interferences, etc.), will be particularly suitable to measure the degradation of material properties through the thickness due to the small geometry and low interference with the base material.

2. Experimental Tests

2.1. Set-Up

The experiments consist of flat plates 200mm square, and different thicknesses corresponding to 12, 20, 30 and 50 plies, with UD carbon fiber and thermoset matrix (Epoxy) AS4/8552, with $[0_{2n}, 90_{2n}, 0_n]_S$ lay-up.

The laminates were placed on a tripod, over an asbestos plate allowing the heat flux just through a little central area. At Figure 1 the experimental set-up can be observed, with the simply supported laminate and the flame exposed area enclosed by the asbestos plate.

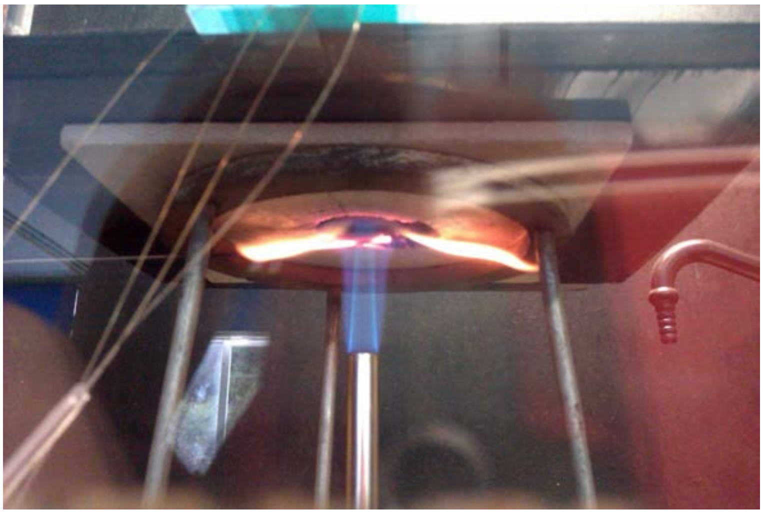

Figure 1. Experimental set-up of the composite material laminate exposed to fire.

As seen on Figure 2, sensors consist of both temperature and strain sensor. The temperature sensor is introduced in a 0.5mm diameter brass tube with one end closed and the other one sealed with silicone, in order to isolate thermal from mechanical strains. Mechanical strains can be deduced subtracting the thermal ones from the total strains.

So as to turn wavelength shifts into strain or temperature changes, one nanometer deviation is equivalent to a 97ºC or 813με, considering linear relationship within the expected range.

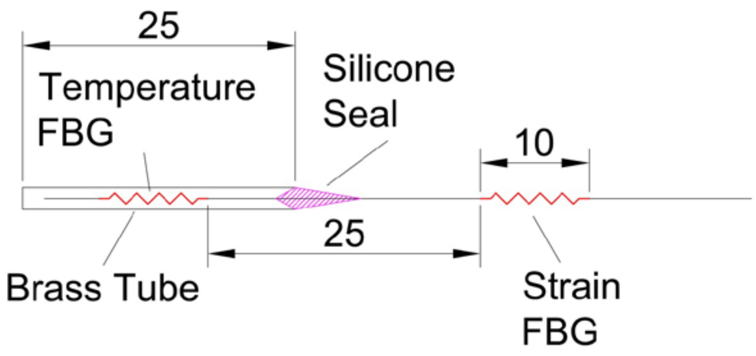

Figure 2. Scheme of temperature and strain FBG sensor.

Sensors are embedded at 10%, 50%, 90% and 100% in the thickness, always parallel to fiber direction, between 0º layers so as to minimize disturbance and ease adaptation during manufacturing process. A scheme of that configuration can be seen on Figure 3. In addition to the 4 FBG sensors, a thermocouple was placed at the top of the flame to verify its temperature, reaching values near to 1000ºC.

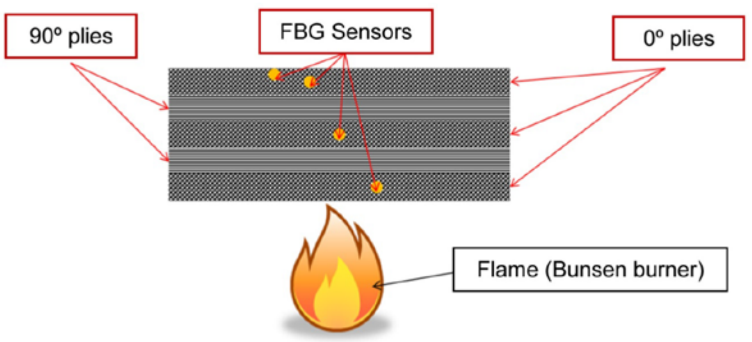

Figure 3. Scheme of positioning of FBG sensors.

2.2. Results

The results of the temperature over time are shown at Figure 4 below, for the 50 plies laminate.

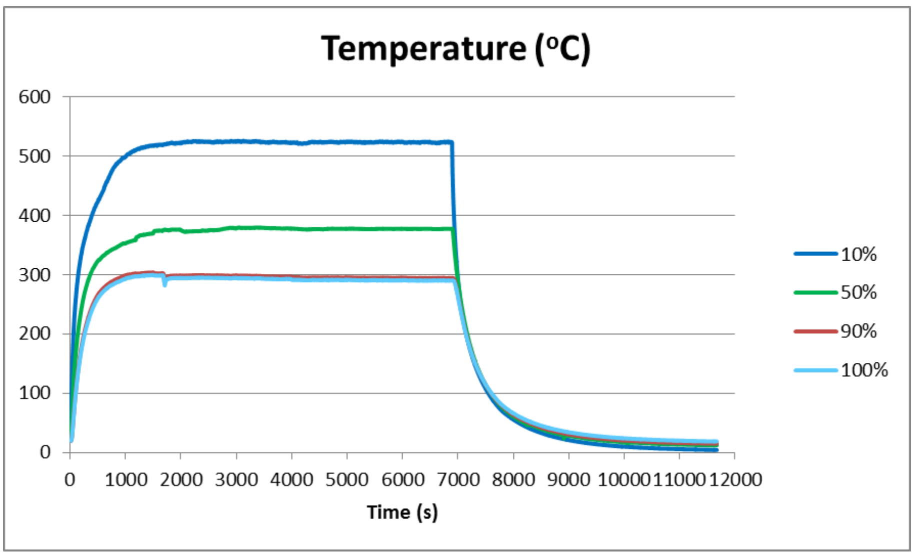

Figure 4. Temperature versus time profile for the 50 plies laminate.

In order to increase the level of stresses that the laminate suffers so as to force a delamination, at one of the tests an aluminum frame was manufactured, which represents a constraint at the four sides, besides using a thinner laminate. This can be seen at Figure 5, and Figure 6 shows the temperature profile for this 30 plies laminate.

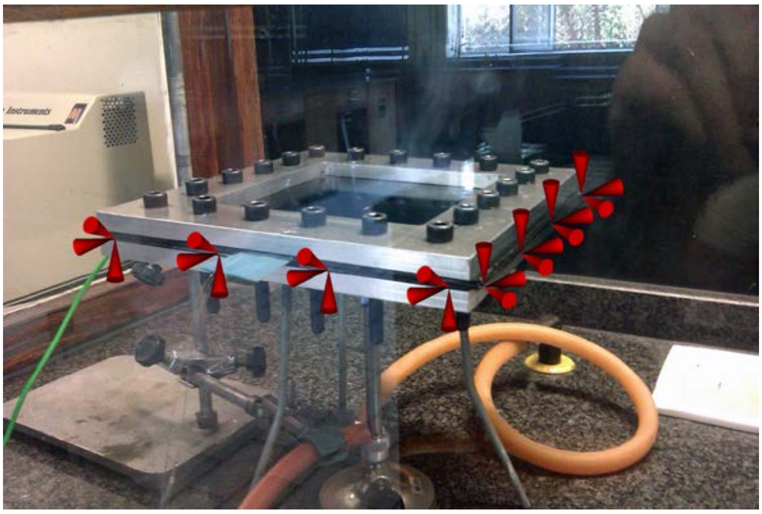

Figure 5. Laminate with aluminum frame that simulates a four sides constraint.

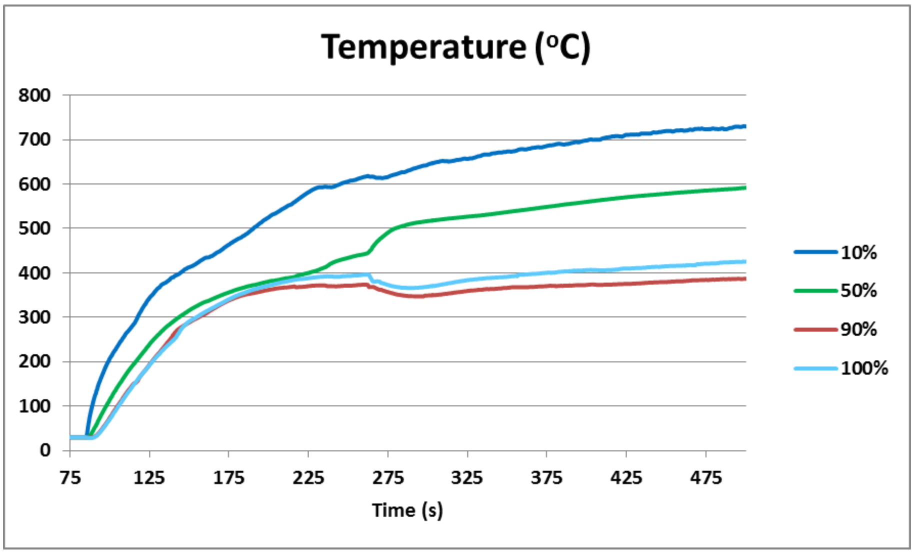

Figure 6. Temperature versus time profile for the 30 plies laminate.

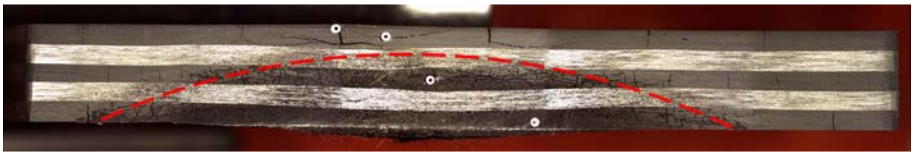

Figure 7. Macrograph after fire test for the 50 plies laminate.

Next macrograph at Figure 8 belongs to the fixed laminate, where inter and intralaminar cracks took place. With this thickness, degradation reached the upper face, while at the 50 plies laminate fire did not go above 70% thickness, as shown on Figure 7 above.

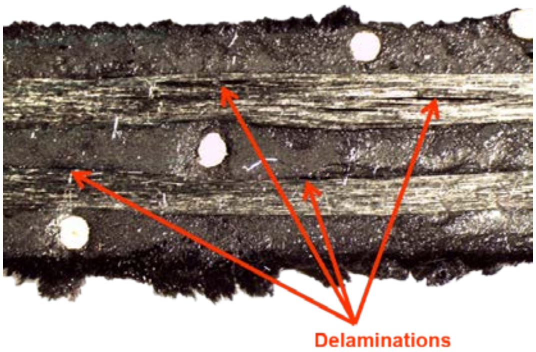

Figure 8. Macrograph after fire test for the 30 plies, four sides fixed laminate.

3. Simulation

3.1. FEM Model details

Simulation was carried out by means of COMSOL®, a commercial multiphysics software which includes, among others, the thermal-structural coupling. The plates are simply supported or fixed, with a 50mm square central area upon which the flame will be simulated.

Material degradation is taken into account above 400ºC, point from which the resin modifies its properties, as shown in Table 1, and will be compared to not degraded material.

Property/Direction	X (0º)	Y (90º)	Z (through thickness)
C.T.E. (α) [με/K]	-0.47	30	30
Thermal Conductivity (K) [W/(m·K)]	5.5	If T<673.15 0.865 If T>=673.15 ((2.83e-4)*(T-273)+0.0949)	If T<673.15 0.865 If T>=673.15 ((2.83e-4)*(T-273)+0.0949)
Young's Modulus (E) [GPa]	130	If T<673.15 8 If T>=673.15 1	If T<673.15 8 If T>=673.15 1

Table 1. Relevant parameters used in the model

As for thermal boundary conditions, heat flux at the flame area was imposed according to Equation 1:

$$q_0 = h \cdot (T_{ext} - T) \tag{1}$$

with $T_{ext}=1250K$.

At the upper face convective flux is applied, down to room temperature, and at remaining faces thermal isolation will be imposed.

The mesh is built with tetrahedral elements, and it is finer at the central area in order to capture with higher accuracy the thermal transverse gradients.

3.2. Results

Combustion times are simulated till the instant in which tests reached steady state. Calculations were conducted with an i7CPU with 4GB RAM, and they took between 4 and 6 minutes to solve.

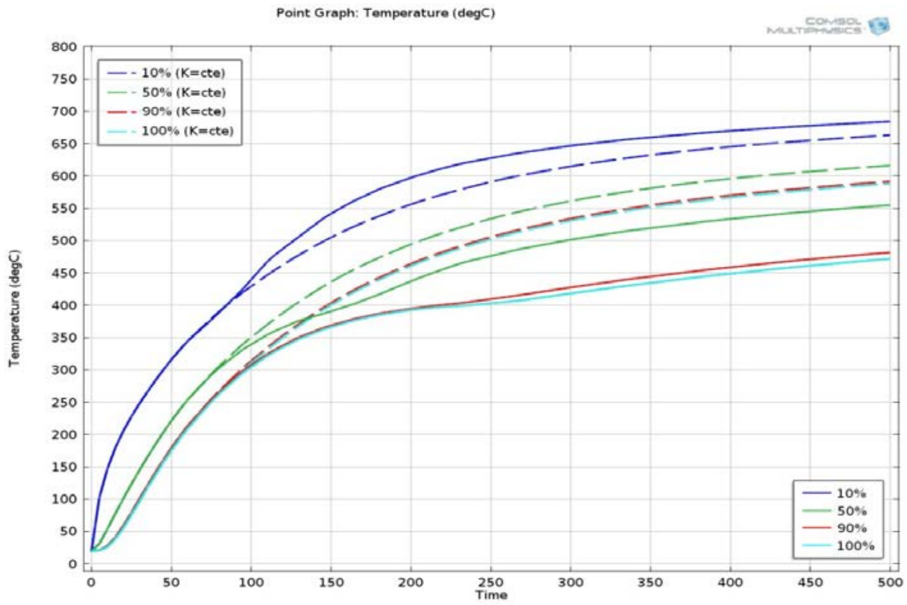

Figure 9. Temperature versus time simulated profile for the 30 plies, 4 sides fixed laminate. Continuous line corresponds to material with degradation condition, while dashed is for non-degraded.

At Figure 9 above, the evolution of the temperature over time can be observed, for material both with and without degradation in the case of 30 plies laminate, where the four sensors reach 400ºC (temperature at which degradation takes place).

Next figures, Figure 10 and Figure 11 show, respectively, temperature isosurfaces for the 50 plies laminate, where the most remarkable feature is the directionality of the fiber properties, since at 0 direction the heat propagation is higher; and the "y" component of the stress tensor of the 30 plies laminate, where the influence of the constraints appears at a strip approximately as wide as the central area, where compression stresses due to thermal expansion exist.

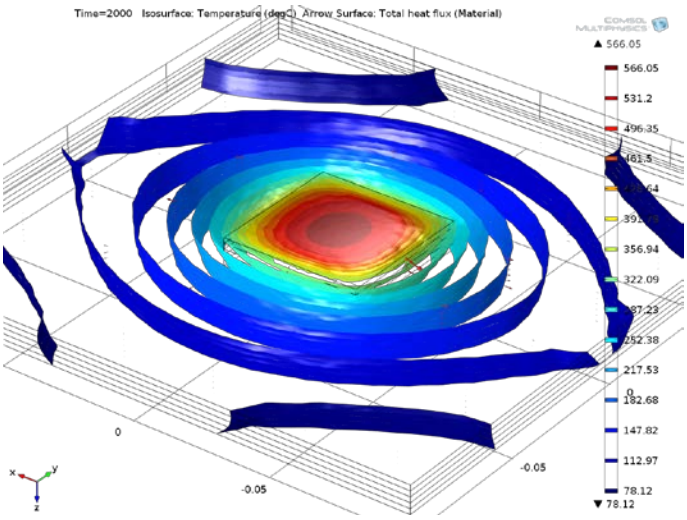

Figure 10. Temperature isosurfaces for the 50 plies laminate.

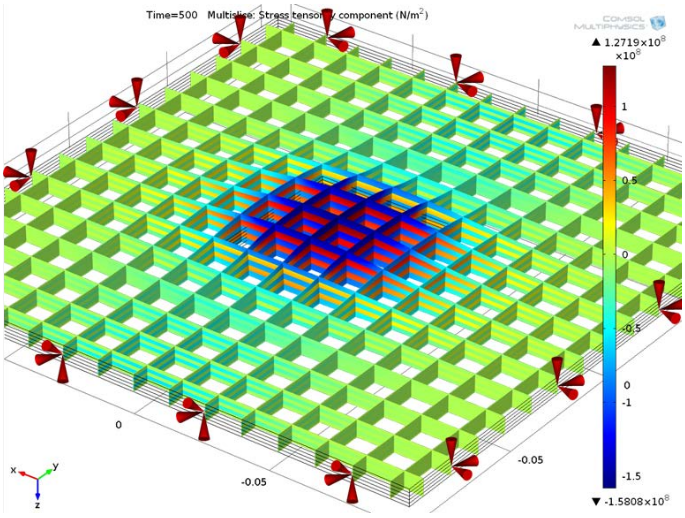

Figure 11. Stress tensor, 'y' component, for the 30 plies, 4 sides fixed laminate.

4. Comparison between experimental and numeric model

Comparison results can be observed at Figure 12 below, with a high degree of similarity between test and numeric model, although the steady state at the model is not reached as fast as at the experiment.

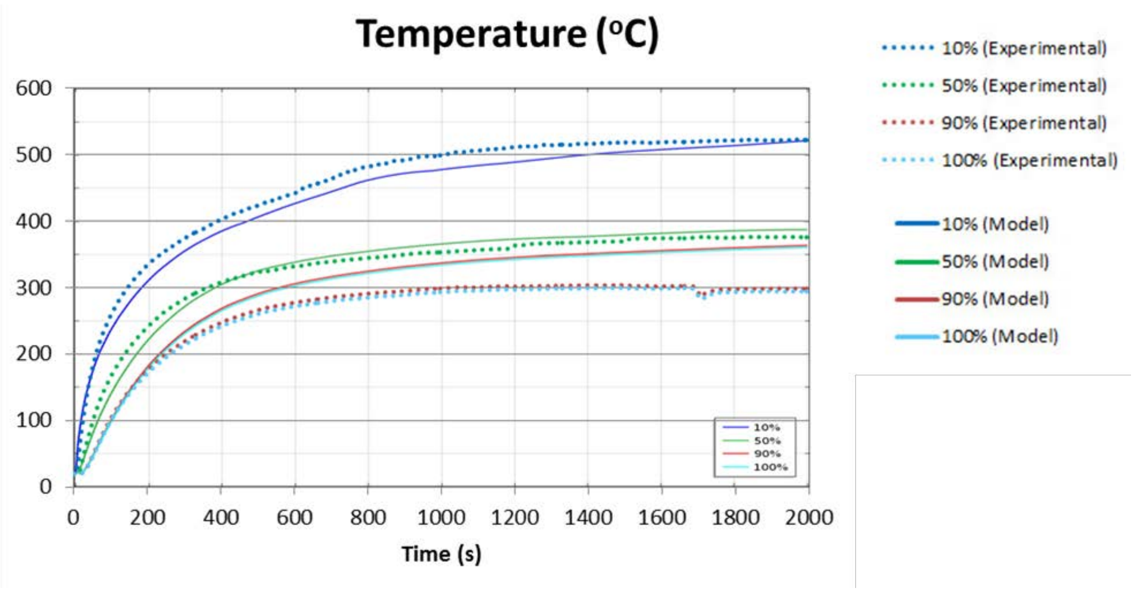

Figure 12. Comparison between experimental (dashed) and numeric model (continuous), for the 50 plies plate.

Figure 13 on next page, which is a photo of the coupon once the tests are finished, remembers the temperature isosurfaces from the numeric model.

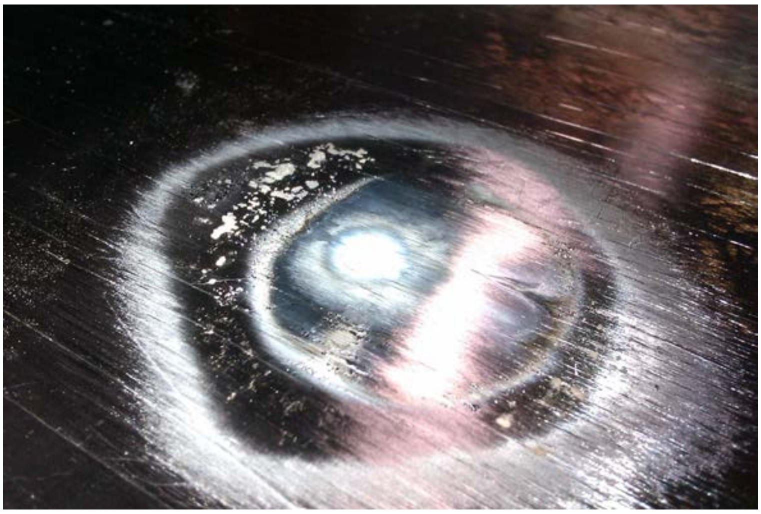

Figure 13. Photo of the degraded material after the test.

5. Conclusions

There is a high degree of similarity between experimental and numerical results, even though it is difficult to precisely identify the material properties, specially thermal ones, because the poor literature concerning.

Two phenomena are critical about heat transmission: polymer material degradation, and the possible occurrence of delaminations. At simply supported laminates degradation is dominant, since stresses are limited because the plate is not fixed. In the case of fixed plate, stresses reached were enough to lead to delaminations. Both phenomena exert an important role from the time in which they appear, limiting maximum reachable temperatures.

Finally, FBG sensors have successfully proved to be able to monitor thermal gradients with very low interferences or weight increase, which otherwise are difficult to measure with conventional sensors or those based on surface techniques.

References

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