Physical modelling of an aeronautical composite in fire

Pauline Tranchard, Fabienne Samyn, Sophie Duquesne, Jean-Luc Montes, Serge Bourbigot

PHYSICAL MODELLING OF AN AERONAUTICAL COMPOSITE IN FIRE

P. TRANCHARD[1], F. SAMYN[1], S. DUQUESNE[1], J-L. MONTES[2], S. BOURBIGOT[1]

[1] R_2Fire group, UMET UMR 8207, ENSCL, University of Lille, Villeneuve d'Ascq, France
[2] Thermal Tech Center, ESCSAT, AIRBUS Operation S.A.S, 316 Route de Bayonne – 31060 Toulouse, France

ABSTRACT

The evaluation of fire behaviour of structural composites is done through experimental tests which are time consuming and costly for the aircraft manufacturers (e.g. ISO 2685 and burnthrough test). Concurrently, the amount of composites in aircraft structures has increased and each type of material has to be fire evaluated accordingly. Currently, the numerical simulation is largely used during the development phase of an aircraft. So, simulation tools are under-development to predict the thermophysical behaviour of composite exposed to fire. Hence it is paramount to explore in detail the behaviour of composites upon fire in order to secure the design and the certification tests to match with the aircraft master planning.

INTRODUCTION

An aircraft in fire is a rare event which can lead to catastrophic consequences for the integrity of the plane and its passengers. The aircraft are thus knowingly dimensioned and have to response to a large number of fire requirements defined by the certification Authorities. Tests, called certification tests, using reduced size of structure panels and standardized burners, are requested from the airframe manufacturers and their partners to show the respect of these requirements. The development of predictive tools of the thermophysical behaviour of the composite exposed to fire is an ambitious and very challenging objective.

The strategy of most authors to get a thermophysical model of composite in fire is to extend the model developed for wood. The wood being a natural composite, it can be considered as similar to thermoset composite for a numerical approach [1]. Generally, a basic model can be used to predict the thermal response of composite submitted to fire. It contains the heat diffusion equation modified by the addition of the decomposition term [2] and sometimes the migration of gases released from the decomposition through the material [3]. Sophisticated models are also reported in the literature [4] but some of them do not succeed to model the fire behaviour of the composites due to the difficulty to obtain inputs. One of the major issues with the use of those complete models is the adequacy of the available data to use as input. Indeed, the more sophisticated is the model, the more input data have to be determined. Moreover in case of physical modelling, the authors have to characterise all these parameters up to high temperature (superior to 250°C).

In case of carbon epoxy composite directly impacted by a flame, previous studies have shown that a basic model is not sufficient to predict the fire response [5-7]. The goal of these studies was to predict a burnthrough time or a temperature profile at different locations (at the surface and in the sample). All these authors have concluded that other phenomena have to be taken into account in the modelling of carbon/epoxy composite in fire. That is why it is also paramount to well understand how the material behaves before any modelling.

Our research is focused on the development of a model of the thermophysical behaviour of a carbon epoxy exposed to fire. A 3D thermochemical model has been previously developed [4]. The numerical results are obtained using a commercial finite element code with a dedicated module named Samcef Amaryllis. This model is composed of three main equations namely the energy equation, the rate of decomposition and the continuity equation. A multi-reaction kinetic model is used for predicting the decomposition of the material. A steady state mass balance equation permits to get the pressure. Finally, the last degree of freedom is the temperature calculated using the heat balance equation. The material starts from a virgin state to a (final) degraded state. The degraded state corresponds to a sample which reaches a thermally stable state composed of char and fibre (inert or not).

A phenomenological approach has been chosen using a novel fire test to develop this 3D model. This permits to understand the behaviour of material and to get reliable data to compare to numerical results [8]. This fire test completely appropriated for investigating the behaviour of composites will be thus presented in a first part. Then, the inputs that feed this model which are thermophysical properties measured by using existing and novel characterisation methods will be presented. Finally, this paper will be focused on the comparison between the numerical results and the reliable experimental data from the fire test.

EXPERIMENTAL

The experiments have been performed on an aeronautical carbon epoxy composite which is unidirectional ([0]s) [8]. It will be named UD T700/M21.

A novel fire test has been developed to investigate the thermophysical behaviour of the composite in fire and to get reliable data for the comparison with numerical results [8]. During a single test (Figure 1), both condensed and gas phases can be simultaneously studied measuring the temperature profile and the mass loss and studying the nature and quantity of volatile gaseous species. The propane-air flame characterised by a heat flux is compliant with heat fluxes of two aeronautical certification fire tests: ISO2685:1998 [9] and FAR25.856(b):2003 [10]. In this paper, the test consists of impacting a 150x150mm² sample by a propane flame at 1100°C and with a calibrated heat flux of 116kW/m² (Figure 2). The goal of this test is to well understand the fire behaviour of material and to get reliable data for the comparison with numerical results.

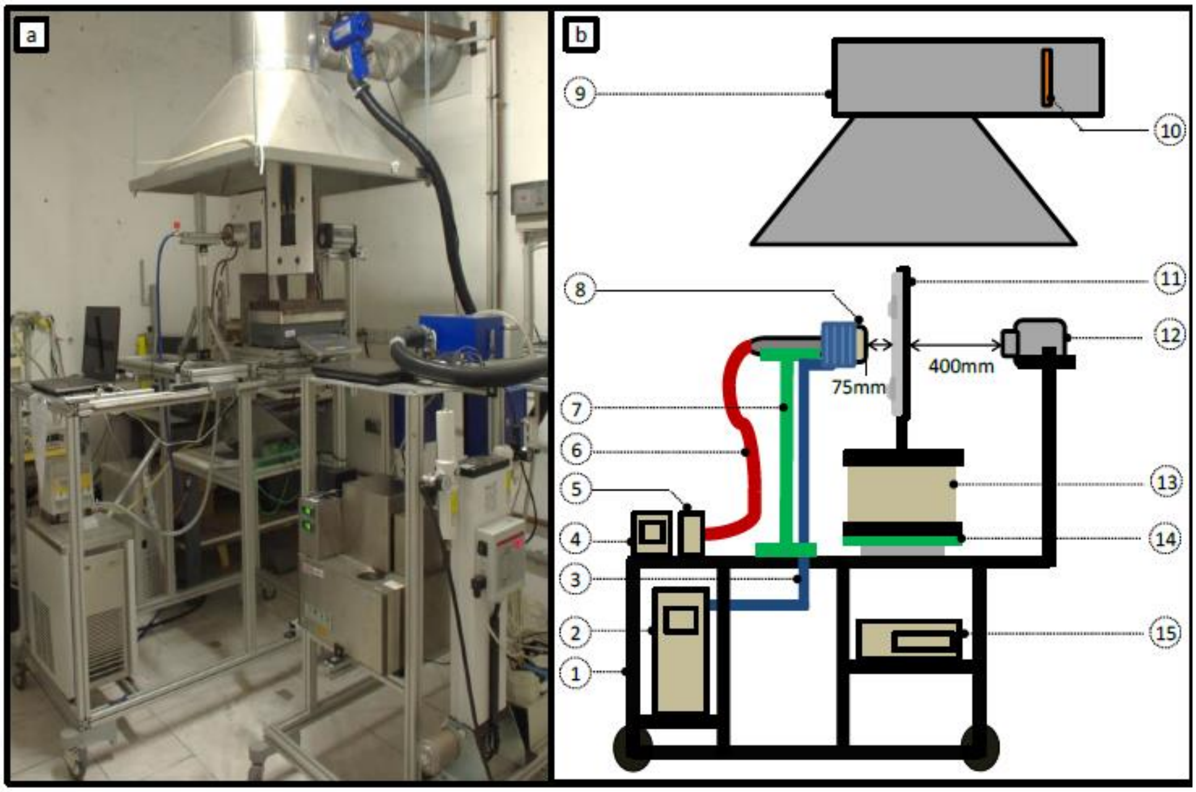

Figure 1: Picture (a) and scheme (b) of the novel test bench [8]
(1) Test bench frame, (2) Cooling thermostat, (3) Copper coil cooler, (4) Propane thermocontroller, (5) Propane flowmeter, (6) Propane gas line, (7) Burner support, (8) Propane flame burner, (9) Hood, (10) Ring sampler, (11) Coupon support, (12) Infrared (IR) camera, (13) Precision balance, (14) Balance support, (15) Data acquisition device

Figure 2: Picture of the burner impacting a composite material

In order to develop a model able to describe the behaviour of composites in fire, it is necessary to get the physical properties of UD T700/M21 at high temperature (superior to the decomposition temperature). All the most sensitive input parameters have been thus determined such as the kinetic decomposition model and the thermophysical properties. In details, after determining the density results, the kinetic decomposition model is determined based on thermal analysis such as thermogravimetric analysis coupled with gas analysis. Afterwards, the effective specific heat capacity and thermal conductivity tensor are determined for two states of material (virgin and degraded state) as a function of the temperature using the simultaneous thermal analysis (STA) and the laser flash analysis (LFA). A law of mixture is then applied between both states of material as a function of a decomposition degree. In addition, the heats of decomposition are calculated based on the STA measurements. The methods used to determine some properties are summarized in Table 1.

Table 1: Equipment used to determine the input properties necessary for modelling [4]

Properties			Methods used
Name	Expression	Unit	
Virgin density	$\rho_0 = \frac{m_0}{V}$	[kg/m^3]	High precision balance + calliper
Degraded density	$\rho_e = \frac{m_e}{V}$	[kg/m^3]	High precision balance + calliper
Arrhenius parameters	A_i, E_i, n_i	[1/s, J/mol, -]	Kinetic analysis based on numerical methods (TG curves)
Virgin specific heat capacity	C_{p_v}	[J/kg.K]	Modulated DSC up to the decomposition temperature - reversing signal
Degraded specific heat capacity	C_{p_e}	[J/kg.K]	Modulated DSC up to 1200°C – reversing signal
Heats of decomposition	Q_{d_i}	[J/kg]	Modulated DSC up to 1200°C – non-reversing signal
Tensor of the virgin thermal conductivity	Λ_v	[W/m.K]	Measurement of the thermal diffusivity using LFA in the three main directions
Tensor of the degraded thermal conductivity	Λ_e	[W/m.K]	Measurement of the thermal diffusivity using LFA in the three main directions

We have investigated the behaviour of the UD T700/M21 when exposed to fire [8] and all inputs for the model have been measured and established [4]. Thus, the purpose of the next part is to compare the reliable experimental data to the numerical simulation.

RESULTS AND DISCUSSION

In this part, the numerical results of the composite are compared to the measured mass and the degraded area. First, a comparison between the predicted and measured masses has been performed and presented on Figure 3. The tests starts immediately after the calibration of the burner and an UD T700/M21 sample is impacted by the flame during 300s of test duration.

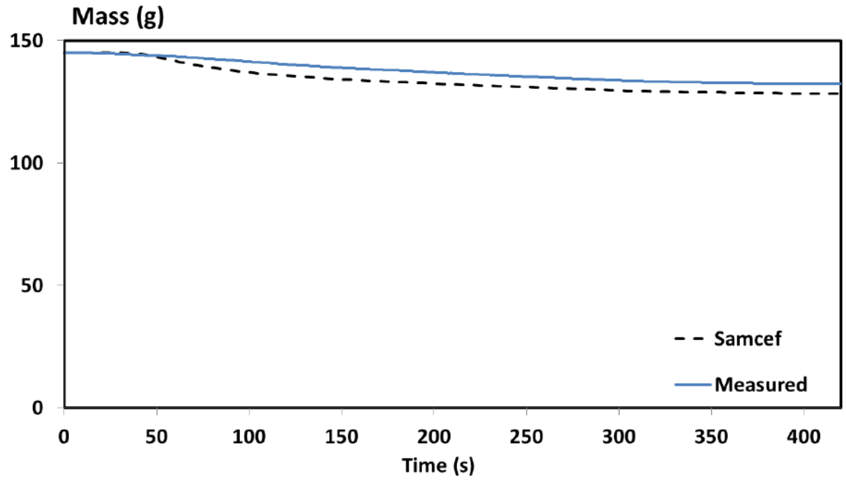

Figure 3: Comparison of the experimental and numerical results of the mass measurement when the T700/M21 is exposed to fire [4]

A good agreement is obtained between the predicted and measured mass of the T700/M21 composite. A maximum error of 3% is obtained between both curves on Figure 3. Therefore, the prediction of the mass is considered as acceptable.

To go further in the study, images of the coupons after 420s of test duration (during the cooling of the sample) and the numerical damage front are compared on Figure 4.

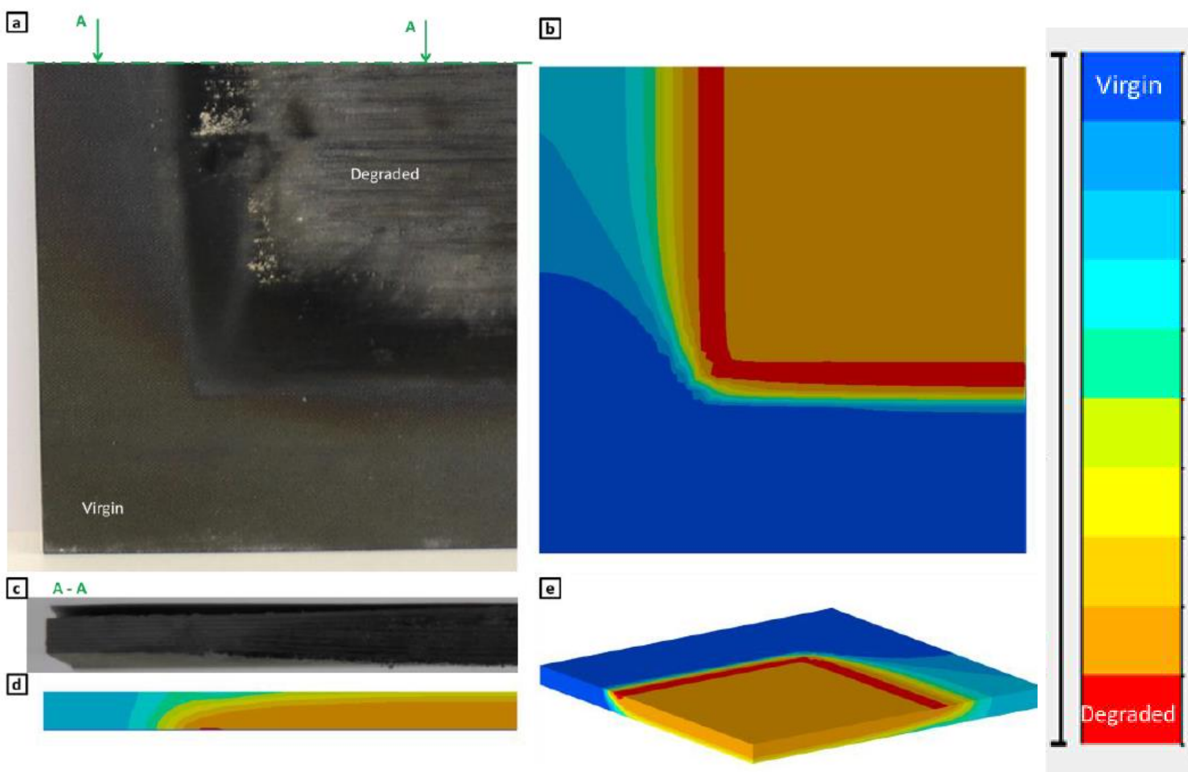

Figure 4: Modelling results from Samcef V.s. data visually observed of the damage front of the UD T700/M21 composite at the exposed face a) & b), section A-A c) & d) and, in 3D view e) [4]

We clearly observe that the material is degraded at the exposed surface on Figure 4a) and slightly degraded under the insulated plate. The damage front follows the thermal conductive heat transfer along the fibre direction (0°) of the UD T700/M21. It is not uniform through the thickness of the material (Figure 4c)). Indeed, the damage front is less important at the rear face of the sample. The same observations can be performed on the numerical results (Figure 4b),c) & d)). These numerical results provide information on the damage front which is higher on the border of the 100x100mm² exposed surface (red part). Figure 4e) permits additionally to show the non-symmetric behaviour of the UD T700/M21 exposed to fire. Therefore, even if the mass is slightly overestimated, the final state of the UD T700/M21 is predicted by the 3D thermochemical model.

CONCLUSIONS

A novel fire test permits to get precise and reliable data to compare to numerical results from a developed thermochemical model. To feed this model, the characterisation of all the most sensitive thermophysical properties has been done using known and innovative methodologies. Notably, we have determined (i) the anisotropic thermal conductivity tensor and the specific heat capacity of a carbon epoxy as a function of the decomposition degree and of the temperature up to 1000°C; (ii) a pragmatic multistep kinetic decomposition model; (iii) the heats of decomposition as a function of the decomposition degree; and (iv) the specific heat capacity of gases as a function of the temperature up to 1000°C. Finally, the comparison between the experimental and numerical results reveals the capability of this model to predict the degraded area of the carbon epoxy material.

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