# FIRE BEHAVIOUR OF CARBON FIBRE COMPOSITES UNDER LOAD

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## Abstract

The complex behaviour of composite materials is an interesting challenge to accurate modelling of their response to fire. Important phenomena include resin decomposition, with its associated volatile evolution as well as non-ideal transport properties of the constituents, most notably carbon fibre. There is a general lack of useful information on these properties. This paper will discuss modelling issues and describe how high quality information can be obtained from small-scale, relatively low cost tests.

## 1. Introduction

Modelling the response of composite materials to fire[1] is hindered by their complex material behaviour, which involves decomposition, gas evolution and non-ideal transport properties[1-9]. This is compounded by an absence of useful experimental information relating to these properties. Many previous studies of the structural response of composites to fire have involved non-aerospace glass fibre-based composites[1-9]. However the rapidly expanding use of advanced composites in civil aircraft applications has increased the need to effectively model the fire response[4,5,8] in a number of critical situations such as engine and post-crash fires.

Previous quantitative studies of composites under load in fire have taken place in a relatively small number of laboratories around the world, including the UK[2,3], Germany[4,5], Switzerland[6], the USA[7,8] and Australia[1-3,9]. The aim of these studies has been to generate high quality information from relatively small-scale, low cost tests. This contrasts with the philosophy employed in industry for the fire resistance qualification of structures, which involves large-scale testing. The purpose of the present paper is to encourage more widespread use of small-scale measurements for characterizing the fire response of CFRP under load, as well as the use of these test results in modelling situations. The research reported here relates to work in progress carried out in the EU 7th Framework FIRE-RESIST partnership.

## 2. Measuring Fire Response Under Load

It is possible to characterise the response of CFRP under load in fire using tests with a loading frame, as in figure 1, similar to the ones that would normally be used for the measurement of mechanical properties[1-3,8,10]. A test is shown under way in figure 2. The heat flux source may be electrical or, as in the present case, a calibrated propane burner and there must be adequate fume extraction facilities above the fire exposure area. There is generally more interest in compression than tension because compressive failure, being a resin-dependent phenomenon, occurs more rapidly and is often the performance-limiting parameter in composite structures exposed to fire. For tests in compression it is often convenient to employ an anti-buckling frame to enable reasonably high compressive strains, comparable to those experienced in use, to be imposed without global buckling occurring.

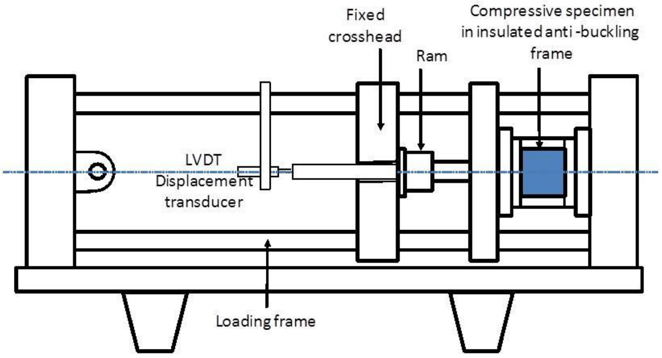

**Figure 1.** Compressive/tensile loading frame for with fire exposure under load. Configuration shown is for fire exposure under compressive load, with anti-buckling frame.

**Figure 2.** Fire exposure test under compressive load on a 100 mm square CFRP sample, at 116 kW/m$^2$.

Figure 3 shows the relationship between the imposed initial compressive strain and the time-to-failure for quasi-isotropic CFRP laminates of different thickness exposed to a heat flux of 116 kW/m$^2$ using the calibrated propane burner shown in figure 2. It is often convenient to express the test results in the form of ‘stress-rupture’ curves of this type. If the load parameter is expressed as compressive strain, rather than stress, the curves are more broadly applicable to CFRP laminates employing different ply architectures approximation. However it should be noted that it is the load level, not the strain, that is held constant during the test.

Figure 4 shows the effect of heat flux on failure time as a function of laminate thickness at a 600 compressive microstrain. The following empirical power law relation in laminate thickness, *b*, heat flux, *q* and applied strain, *e* (expressed as microstrain) was derived using least squares from the results of figures 3 and 4.

$$t_f = 1{,}301\ b^{1.9}\ q^{-0.54}\ e^{0.55} \qquad (1)$$

It is interesting to note that the exponent of 1.9 in thickness is close to 2, reflecting the fact that the time to heat up sections of material is proportional to the square of the thickness. This approximate relationship is probably of sufficient general accuracy to provide a good first estimate of the failure time of most CFRP aerospace structures in the range of thickness, heat flux and strain considered here. In many cases, this first, approximate estimate may be all that is needed to make a decision as to whether the fire performance is acceptable. It is clear from the figures that the times to failure are short, being determined essentially by the time taken for a proportion of the load-bearing material to reach its glass transition temperature.

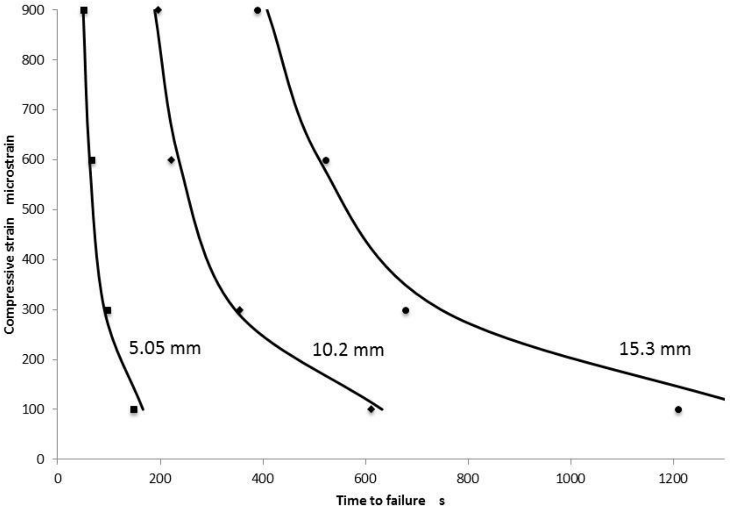

**Figure 3.** Effect of compressive strain on time to failure for quasi-isotropic CFRP laminates of different thickness at a one-sided heat flux of 116 $kWm^{-2}$.

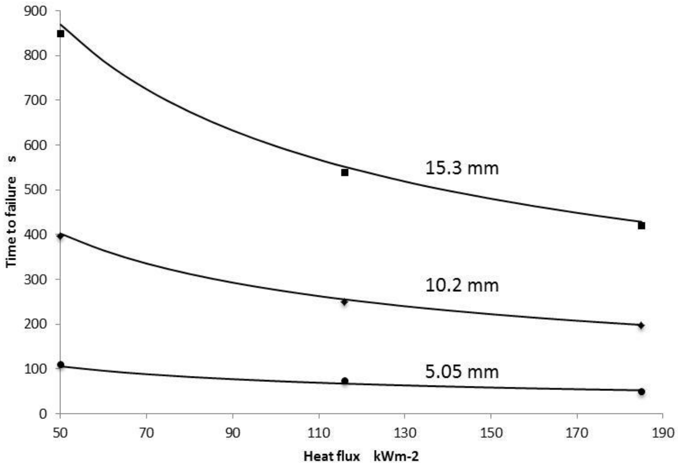

**Figure 4.** Effect of heat flux on time to failure of laminates of quasi-isotropic CFRP laminates of different thickness at a compressive strain of 600 microstrain.

## 3. Modelling the Thermal Response

The key phenomena that occur when a composite is exposed to fire[1-3] are shown in figure 5. The effect of resin decomposition is usually significant. It can be modelled either by an Arrhenius-type law or sometimes by the simplifying assumption that the decomposition state is a straightforward function of temperature as determined, for instance, directly from TGA measurements. The decomposition reaction is usually endothermic, which needs to be taken into account. Finally, resin decomposition produces gases, which travel through the structure towards the hot face, transporting heat in a direction against to the thermal gradient. The simplest relationship that provides the basic capability of describing these effects is the Henderson Equation[1-3,7], which, in one-dimensional form, is:

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left( k \frac{\partial T}{\partial x} \right) - \rho \frac{\partial M}{\partial t}\left( Q_P + h_C - h_G \right) - M_G \frac{\partial}{\partial x} h_G \qquad (2)$$

here: $T$, $t$ and $x$ are temperature, time and through-thickness coordinates, respectively; $\rho$, $C_P$ and $k$ are the density, specific heat and thermal conductivity of the composite; $M_G$ is the mass flux of decomposition volatiles; $h_C$ and $h_G$ are the respective enthalpies of the composite and evolved gas; and $Q_P$ is the endothermic decomposition energy of the resin.

The three terms on the right of Equation (2) relate, respectively, to heat conduction, resin decomposition, and convective heat transport by the volatiles evolved. The material parameters all vary as functions of temperature and resin decomposition. A one dimensional finite difference package, COM-FIRE, was written to solve this equation for a range of different composite systems.

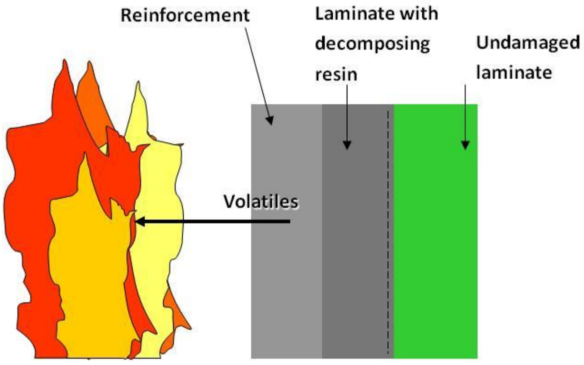

**Figure 5**. The key phenomena that occur when an organic matrix composite material is exposed to fire.

## 4. Modelling Laminate Behaviour as a Function of Fire Exposure

Rigorous modelling of the mechanical behaviour of composites under load in fire currently requires a large number of mechanical property measurements to be made as a function of temperature[1-3]. From stress-strain curves measured over a wide temperature range it has been shown possible to synthesise an effective non-isothermal 'stress-strain' curve for the complete laminate at each point in time during the fire exposure, and thus compute the residual strength, which may be used to predict the failure mode and the onset of failure. Although this approach was successful it is recognised that it will not normally be feasible to carry out such a large number of measurements for every composite system that needs to be modelled. An alternative, simpler, procedure is therefore being developed. It is recognised that many of the resin-dependent properties of a composite material, including the compressive strength, vary in a somewhat similar fashion with temperature. Equation 3 is an empirical relationship, which has been used previously to describe the variation of any particular property with temperature[1-3]:

$$P(T) = 0.5\left(P_U + P_R - \left(P_U - P_R\right)\tanh\left(k\left(T - T'\right)\right)\right) \qquad (3)$$

Here, $P(T)$ refers to a particular property and $P_U$ and $P_R$ are the relaxed and unrelaxed values of that property (i.e. the values at high and low temperature). The factor, $k$, describes the breadth of the transition region, where the property falls with temperature and $T'$ is the temperature of the mid-point of the transition. As mentioned, this relationship has no physical basis but is very convenient to fit. There are rather few thermal constitutive relationships of this type available in the literature for modelling purposes. One alternative, which has some physical basis, is the model proposed by Mahieux and Reifsnider[10]. Both relationships work well in most cases but Equation (3) is sometimes simpler to manipulate.

An additional problem in modelling is the need to determine compressive strength values over a wide temperature range, which is not an easy task. One approach, being considered, is to measure compressive strength at room temperature only, then assume that, being a resin-dependent property, it varies in a similar way with temperature to other easier-to-measure properties such as the ply transverse shear modulus or the interlaminar shear strength. Figure 6 shows a 'normalised' plot based on the mean of all three parameters, which all vary in a similar way, along with the compressive strength. Unfortunately, not all resin-dependent properties are found to vary in the same manner with temperature. This is presumably dependent on the particular constitutive law that relates the composite property to resin properties, a factor that needs further investigation. The ply transverse Young's modulus, for instance, results in curves similar to those in figure 6, but displaced to significantly higher temperatures, in other words with a higher value of the transition mid-point temperature, $T'$. In the current work, property values such as those shown in figure 6 have been chosen.

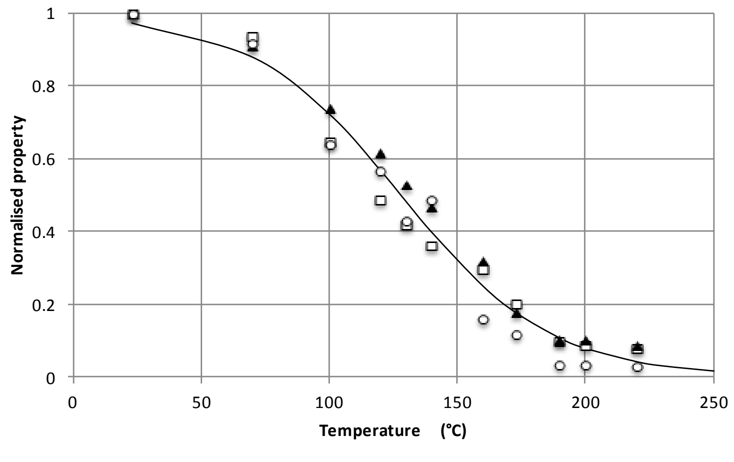

**Figure 6.** Resin-dependent properties for a CFRP unidirectional laminate, correlated according to Equation (3). ▲ interlaminar shear strength; ☐ compression strength; ○ in-plane shear modulus. Data have been normalised to a value of 1 at room temperature.

An example of the COM-FIRE programme output is shown in figure 7 for the case of a 10.3 mm thick quasi-isotropic laminate subject to a heat flux of 116 kW/m$^2$. This shows the temperature field within the laminate at each point in time. Using the temperature function in

Equation (3) it is then possible to determine an average compressive strength through the laminate thickness at each point in time, using an averaging procedure:

$$\overline{\sigma}_C = \frac{1}{b}\int_{x=0}^{x=b} \sigma_c(T)dx \tag{4}$$

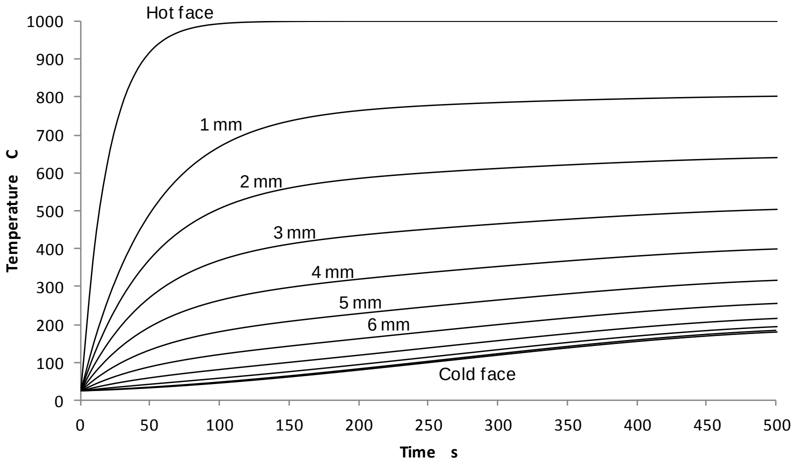

**Figure 7.** Temperature distribution vs. time in a 10.3 mm thick QI laminate subject to a heat flux of 116 kW/m$^2$.

The decline of the average compressive strength with time was determined for the thermal field shown in figure 7 and for two other laminate thicknesses. The result is compared with the measured times to failure (shown in figure 3) in figure 8, right, where it can be seen that there is reasonable agreement between the measured and modelled quantities. Good agreement was also found for the other heat flux values used in the tests. Further work is being carried out on this simplified approach to modelling behaviour under load in fire.

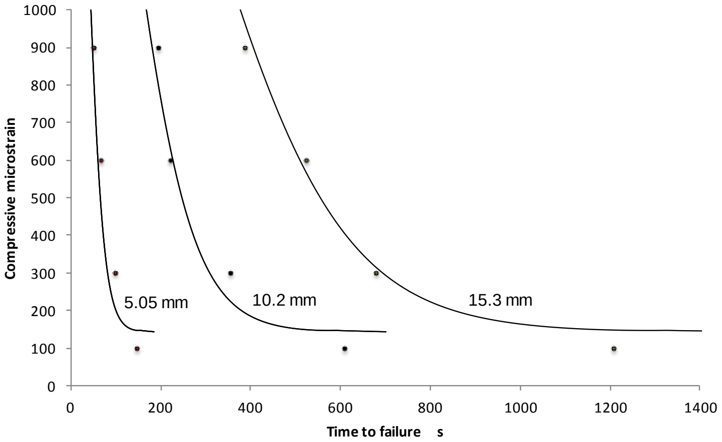

**Figure 8.** Comparison between predicted failure curves (using the data from Figures 6 and 7) with experimental failure values (from Figure 3).

## Conclusions

Characterisation and modelling of the response of advanced composite structures can be achieved based on reproducible time-to-failure measurements involving relatively small-scale samples under controlled conditions. For modelling the response under compressive load it is possible to achieve reasonable accuracy by relating the thermal variation of compressive strength to that of other, more easily measured resin-dependent properties. It also appears possible to make the approximation of calculating and average compressive strength for the section at each point in time.

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