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Numerical Modelling of Thermo-Chemical Degradation of Carbon Fibre Composites (CFCs) due to Laser Ablation

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Abstract

There is a growing interest in using carbon fibre composites (CFCs) as a high tech construction material rather than the more commonly used Aluminium (Al). CFC comprise of long strands of highly conductive carbon fibres impregnated into a poorly conductive polymer matrix.

The damage caused to a piece of CFC due to a lightning strike is very different to what occurs to a piece of Al. To investigate the degradation mechanisms a 2D numerical model has been developed which is designed to predict the damaged caused to a piece of CFC.

Initial verification of the model is conducted by decoupling the thermal physics from the electrical effects and damaging the pieces of CFC by using laser ablation. The predictions from the 2D model provide a reasonable agreement with the experimental laser ablated CFC samples.

Thermal modelling framework

A lightning strike results in the rapid heating of CFC. This occurs on the surface through the radiation from the plasma channel and also by volumetric Joule heating.

The heating causes the CFC to degrade. This happens in two ways, firstly via direct mechanical fracture due to the thermal expansion of the CFC and secondly via thermo-chemical reactions (phase change and pyrolysis).

The study is concentrated on modelling thermo-chemical reactions. A diagram of the main physical processes along with some model simplification are shown in fig.1

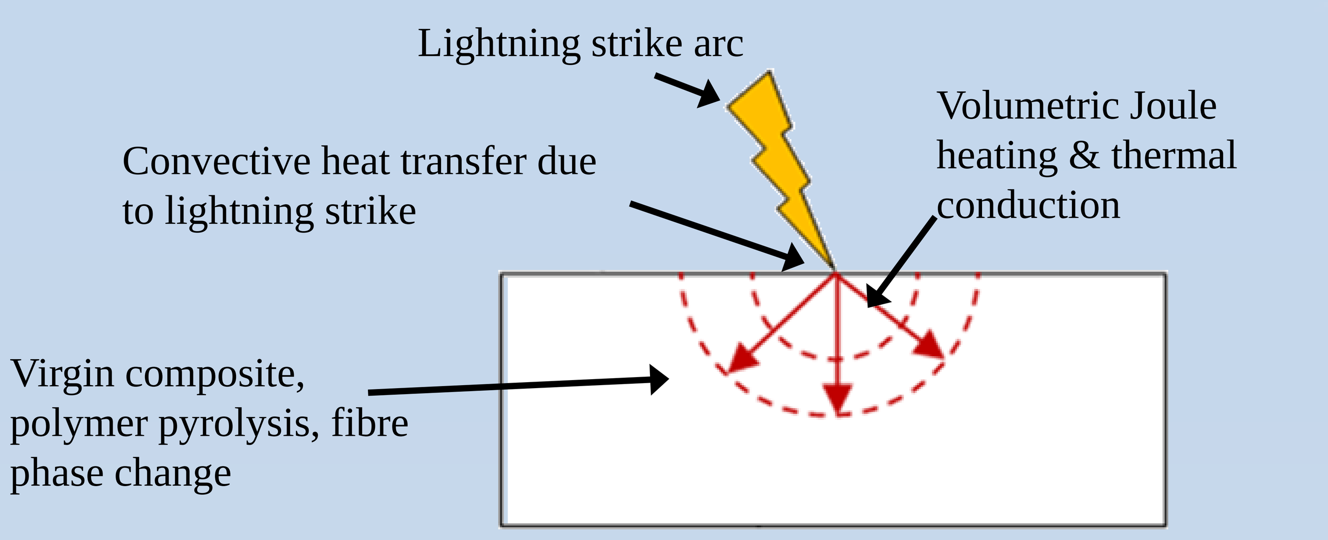

Fig 1: Simplified schematic of the reaction processes in the through thickness direction decomposing polymer

Experimental validation

The initial verification is conducted by decoupling the thermal effects from the electrical. This is done by damaging a piece of CFC with a laser beam.

A sample of CFC is ablated with a 6 Watt laser beam for 180s seconds. The total energy input from the laser is ~ **1 kJ**. Whilst this is comparable to the energy input from the continuous current profile of a lightning strike, the rate of energy deposition is far slower and also the total energy for the entire lightning strike is much greater than this.

The damaged CFC sample was then examined via x-ray tomography to determine the dimensions of the damaged area. Fig.2 shows the X-ray tomography images of laser ablated sample. The X-ray tomography has a resolution of 25µm. The dark regions in the image depict the damaged areas i.e. where material has been removed (polymer and carbon fibers) and the grey regions are undamaged CFC.

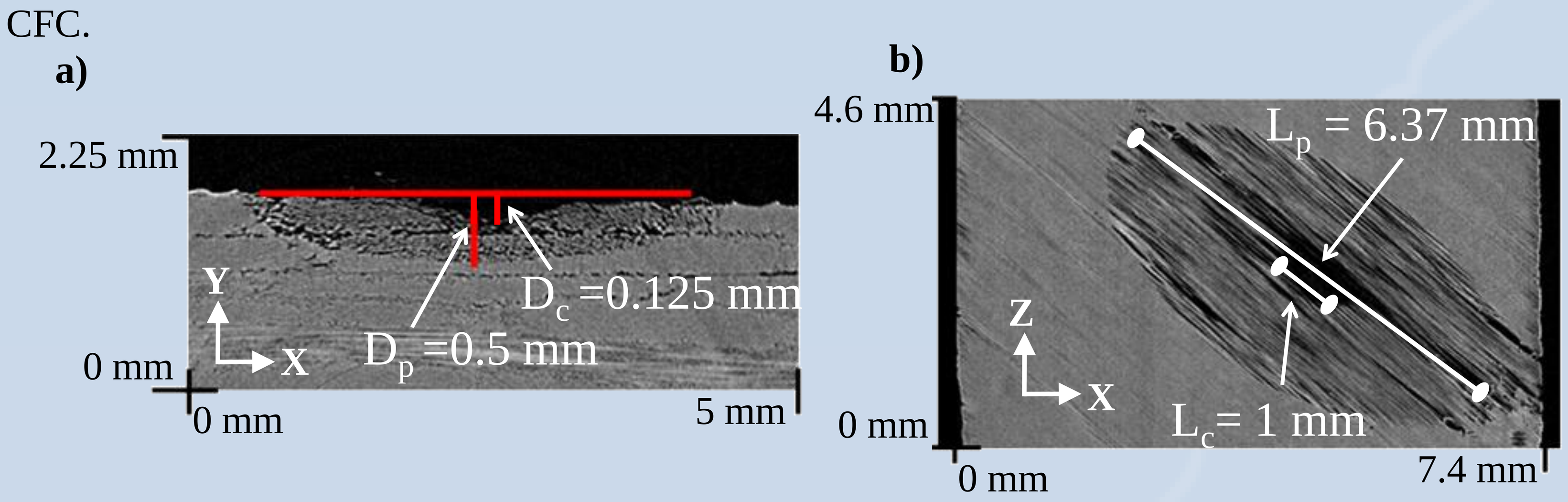

Fig 2: X-ray tomography of experimental damage. a) Cross section view of damage. b) Top down view of damage.

Numerical Model Overview

The numerical model is a bespoke finite volume model. Due to multi-physics within this problem it is difficult to solve it directly. Therefore the model is solved by splitting the different physical aspects up and solving each of them in turn via a segregated solver approach. The key physical aspects of the model are: **Quasi-static DC conduction model**, **Thermal conduction model**, **Polymer degradation model**, **Carbon fibre phase change**, and the **Resultant transport of the gas** produced to the decomposing polymer.

Due to the decoupling of the thermal from the electrical effects in the laser ablation experiment, the model here does not include the **Quasi static DC conduction**. Further more the **gas transport** has not been considered here.

The **thermal conduction** is solved by considering the standard diffusion equation as shown in [1]

The **polymer degradation** has already been studied in detail [2]. The principle method of polymer degradation which is important here is pyrolysis. Polymer **Pyrolysis** can be modelled via the Arrhenius equation [1,2].

The **carbon fibre phase change** has been implemented as post processing to the **thermal conduction** by considering the change in enthalpy of the system, as outlined in [3]

A more detail look at the modelling equations, assumptions and values used in the numerical model can be found in [1]

Model Geometry

The numerical model is designed to replicate the laser experiment discussed previously. The bespoke numerical model is solved as a two dimensional model. The 2D geometry is taken to be a 2D cross section through the CFC. Shown below in Fig.3 is a diagram of the geometry used.

It is worth remarking that by solving the model in 2D, the model being solved here is not exactly the same as the experiment due to the symmetry implied by the 2D limitation. Therefore we expect the predicted damage from the numerical model to be an over estimation.

A piece of CFC is represented in the numerical model by considering it as a homogeneous anisotropic block. This has proven to be accurate an accurate representation [4]. The direction of principle conductivity i.e. the fibre direction is defined along the x axis

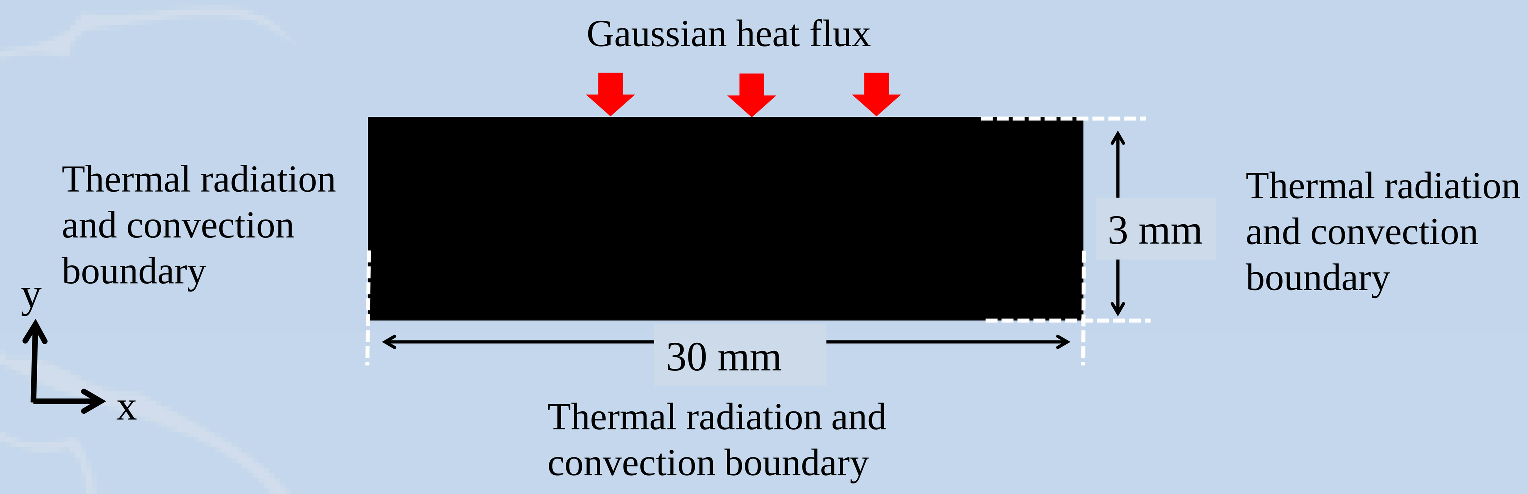

Fig 3: Diagram of the 2D geometry and the boundary conditions used in the numerical model

Numerical Model Predictions

Now consider the predicted spatial extent of the damage from the numerical model. The mass of polymer per unit cell at a time during the simulation is shown in Fig.4. Marked on the Fig.4 is the polymer damage length (L_p) and the Polymer damage depth (D_p). Fig.5 shows how the polymer damage depth (fig.5b) and the polymer damage length (fig.5a) varies as a function of time.

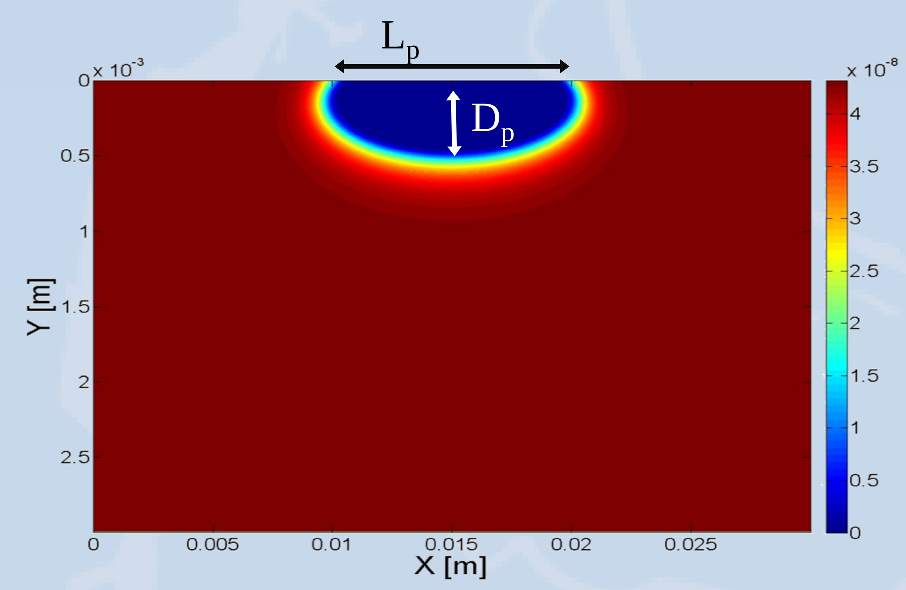

Fig 4: (Above) shows the mass of polymer per unit element [kg] in the model at 100 seconds.

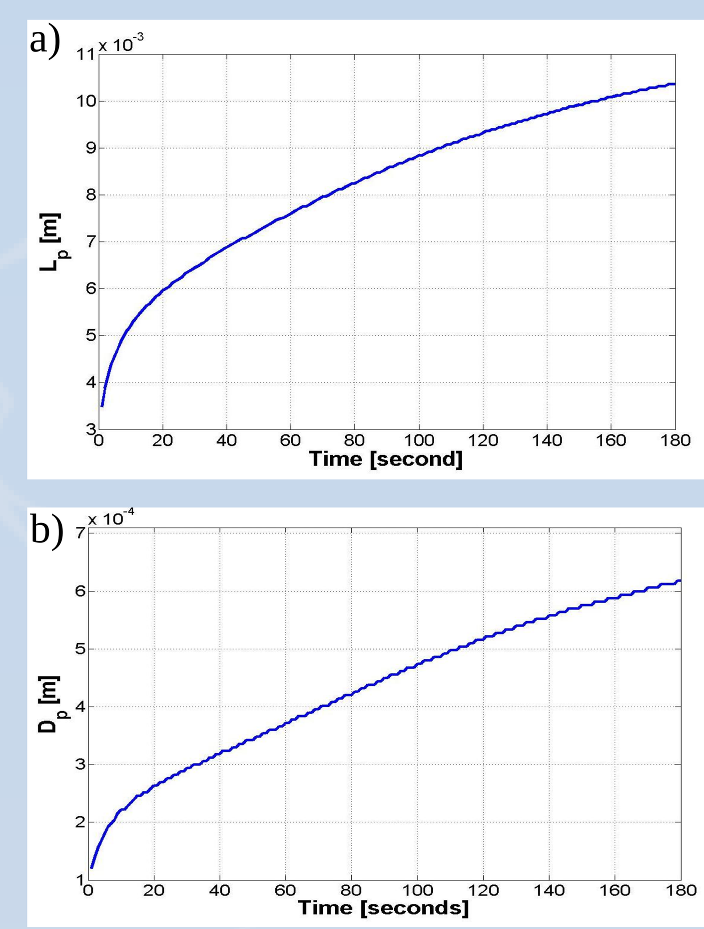

Fig 5: (Right) shows (a) the damage length of polymer (L_p) and (b) the damage depth of the polymer (D_p) as a function of simulation time

Comparison of Results

Shown in table 1 are the results of the spatial extent of the damage predicted by the numerical model compared with the values obtained experimentally from the laser ablation

The polymer damage depth and the fibre damage length and very similar.

The fibre damage depth and the polymer damage length are less comparable.

Despite the limitation of the modelling being in 2D the model appears to be relatively accurate. This is a good indication for the expansion of the model into three dimensions

The accuracy of these results seem indicate that any change in energy due to the gas transport does not appear to have a significant effect on the damage extent of the damage depth.

	Experiment	Bespoke Model
Fibre damage length (L_c)	1 mm	1.12 mm
Fibre damage depth (Dc)	0.125 mm	0.042mm
Polymer damage length (L_p)	6.37 mm	10.3 mm
Polymer damage depth (D_p)	0.5 mm	0.62 mm

Table 1: spatial extent of the damage from the laser ablation experiment and the numerical model.

Conclusions

A framework for predicting the thermal damage caused to a carbon fibre composite due to a lightning strike is suggested. An attempt has then been made to verify the model, by decoupling the thermal and electrical components of the system and conducting a laser ablation experiment. Despite the model only being in 2D and not in 3D, the numerical model does give at least a reasonable agreement with the experimental results.

The next step is to expand the numerical model into three dimensions. With the model in three dimensions a more accurate verification of the model can be done against the experimental results.

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[2] Staggs J.E.J, Heat and mass transport in developing chars, Polymer Degradation and Stability, Vol. 82, 2003, pp 297-307
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