CompTest 2008

Fire Models & Test Methods for Composites

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Composites in Fire

- Polymer matrix composites used increasingly in high fire risk applications.
- Composites must demonstrate low flammability & low smoke toxicity in the event of fire (eg. FAA, IMO). Assumed high structural integrity.
- Fire resistance of composites is not defined by a single material property, but many reactive properties:
  - **Time-to-ignition**
  - **Heat release rate**
  - **Smoke density & toxicity**
  - **Flame spread rate**
  - **Residual mechanical properties**
  - **Etc, etc.**



Composites in Fire

- Fire reaction properties of composites have been studied for 30+ years. Focus on common engineering composites (eg. carbon-epoxy; glass-polyester).

- Fire reactive properties (not related to structural performance) are well known:
  - ✓ **Time-to-ignition**
  - ✓ **Heat release rate**
  - ✓ **Smoke density**
  - ✓ **Flame spread rate**

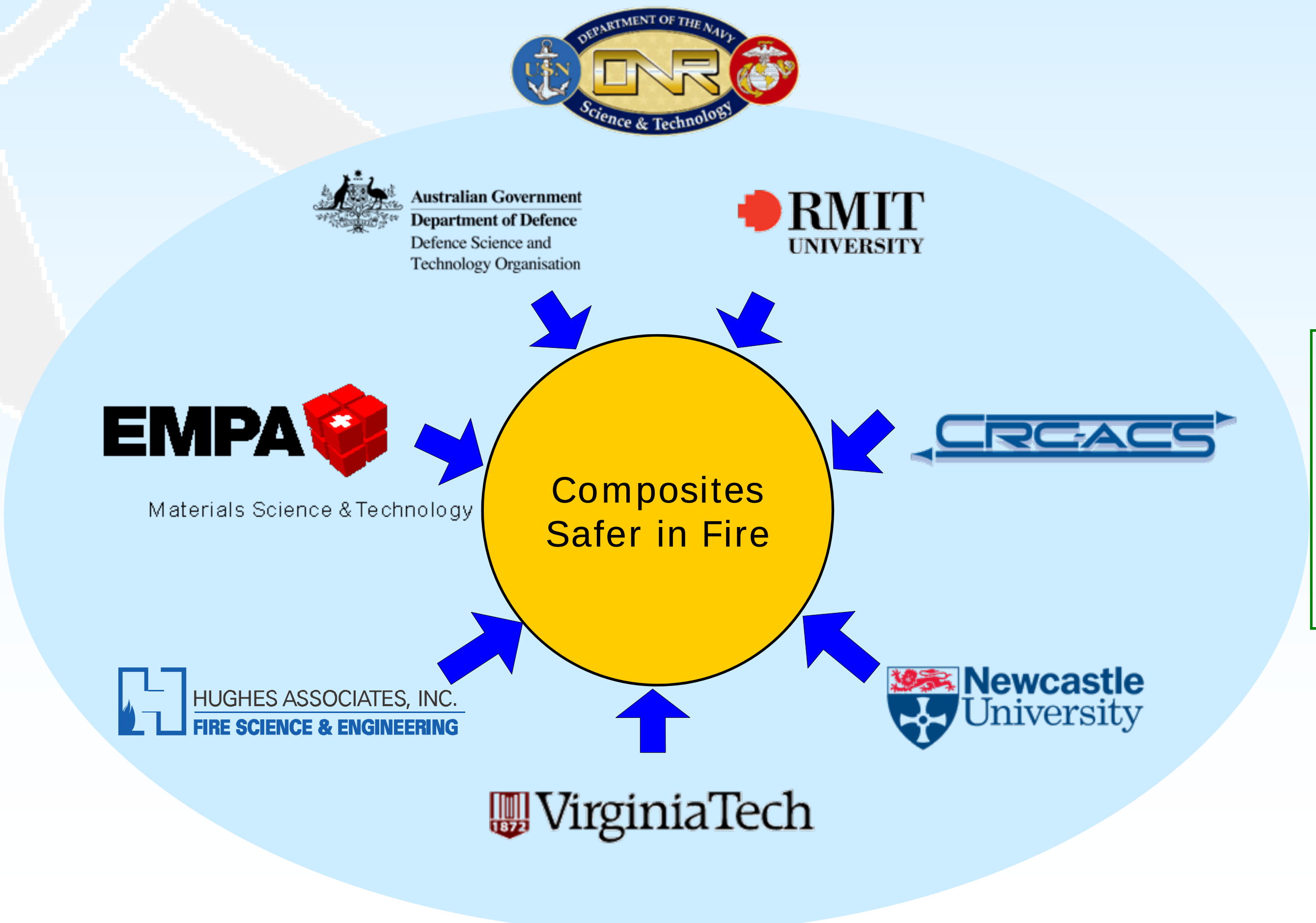
- Large data-bases for these properties determined for many fire scenarios, although mechanistic-based models are lacking.

Composites in Fire

- Structural performance – stiffness, strength, creep – of composites in fire is less understood.
- Well known that thermal softening & decomposition of ***polymer matrix*** plus softening & damage of ***fibre reinforcement*** degrades structural integrity of composites.
- Early fire structural studies based largely on experimental tests *without* consideration of fundamental softening & damage mechanisms nor validated structural integrity models.

Composites in Fire

US Office of Naval Research fund a co-ordinated research program to develop validated models to analyse structural behaviour of composites in fire



USA

Australia

UK

Switzerland

Composites in Fire

Research presented in this paper is a collaborative effort:

- Stefanie Feih *(RMIT)*
- Zenka Mathys *(Defence Science & Technology Organisation)*
- Geoff Gibson *(University of Newcastle-upon-Tyne)*
- Scott Case *(Virginia Tech)*
- Brian Lattimer *(Virginia Tech)*

Presentation Overview

- **Thermal model** of composites in fire
- **Decomposition model** of composites in fire
- Fundamental damage mechanisms in fire
- **Compression models** of composites in fire
- **Tension models** of composites in fire
- Experimental verification of fire models
- **Post-fire models** for composites

Model Overview

Thermal Analysis

⇓

Decomposition Analysis

⇓

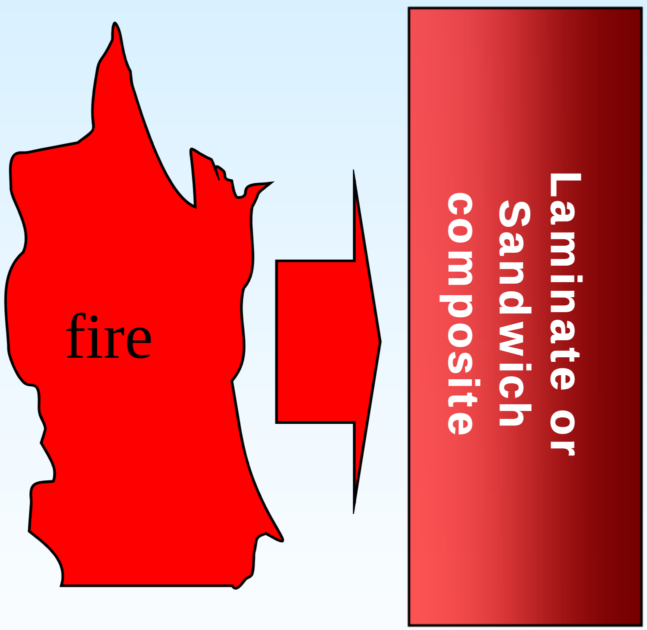
Non-Uniform Property Changes

⇓

Bulk Mechanical Property Changes

⇓

Final Failure: Tension & Compression



Thermal Model

Thermal Analysis

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Decomposition Analysis

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Non-Uniform Property Changes

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Bulk Mechanical Property Changes

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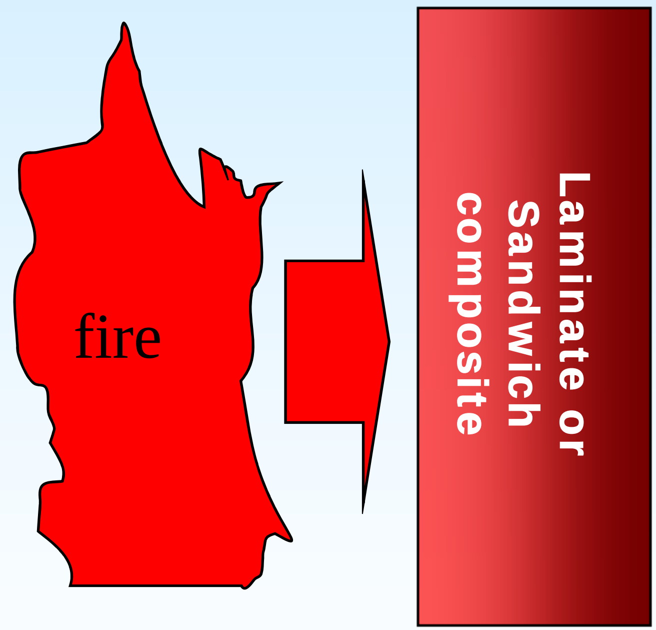
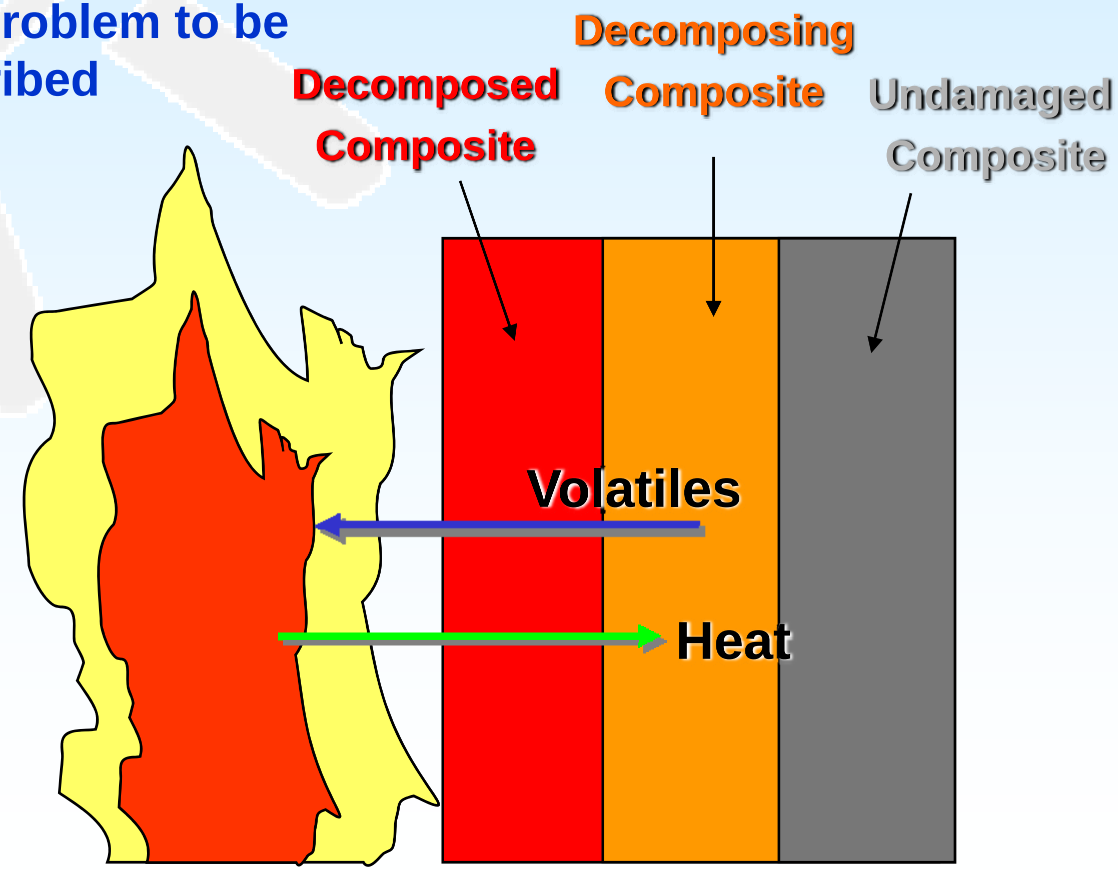
Final Failure: Tension & Compression

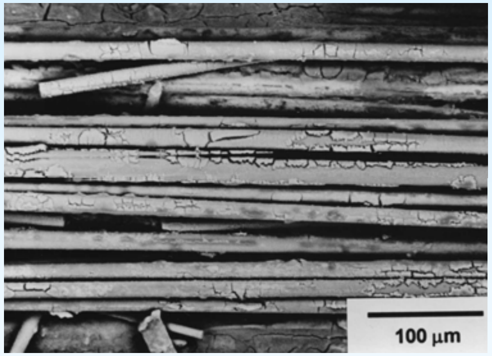


Thermal Model

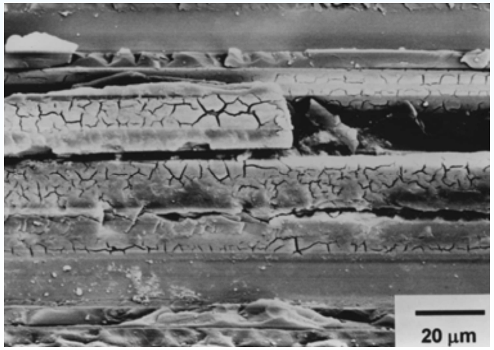
First step in analysis is thermal analysis of polymer laminates & sandwich composites exposed to fire

The problem to be described





Decomposed Composite



Decomposing Composite

Thermal Model

Analysis of thermal response of composites using the Henderson model that considers:

- **heat conduction from flame into composite**
- **decomposition of polymer matrix**
- **flow of decomposition gases from composite into flame**

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \dot{M}_G \frac{\partial}{\partial x} h_G - \rho A\left[\frac{(m - m_f)}{m_o}\right]^n e^{-\frac{E}{RT}}\left(Q_P + h_C - h_G\right)$$

Unsteady State Heat Conduction

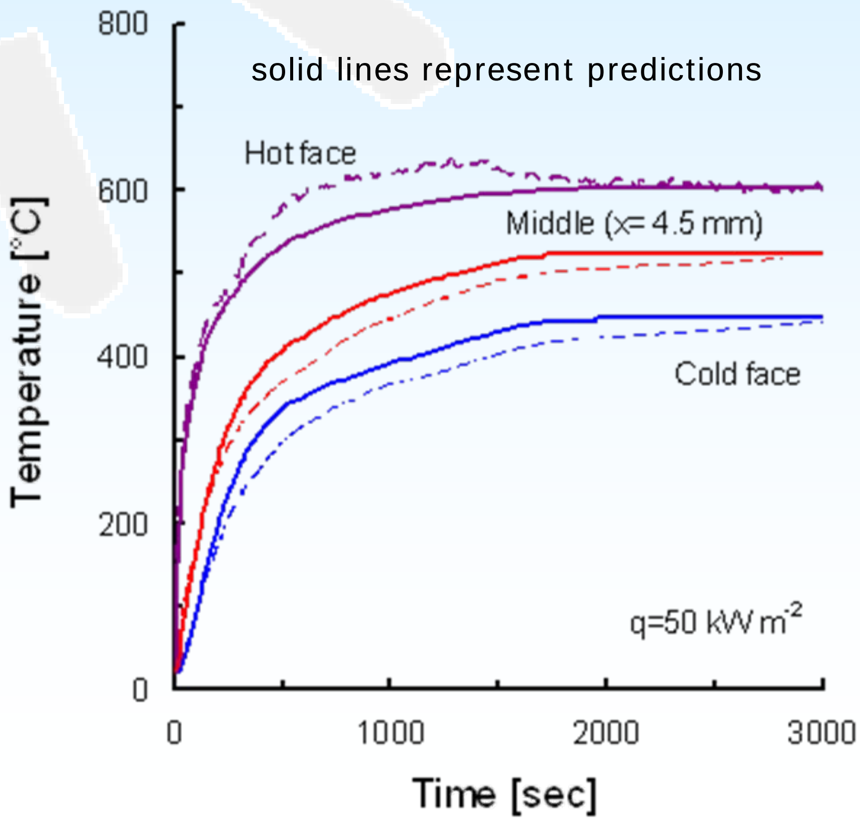
Mass Flux of Volatiles

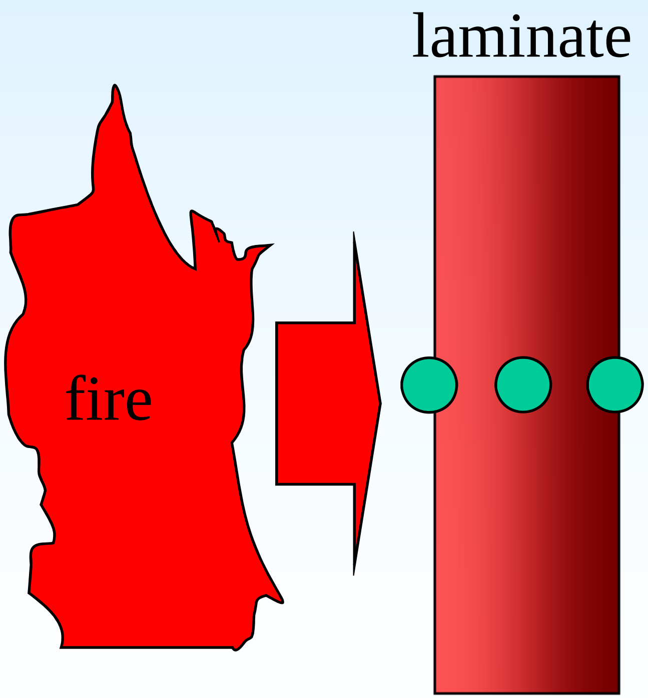
Endothermic Decomposition of Polymer Matrix

Thermal Model

Temperature profile (through-thickness) is calculated for any heat flux condition of the fire.

Model validated for composites tested at heat flux conditions from 10 kW/m^2 (~250^{o}C) to 100 kW/m^2 (~800^{o}C).

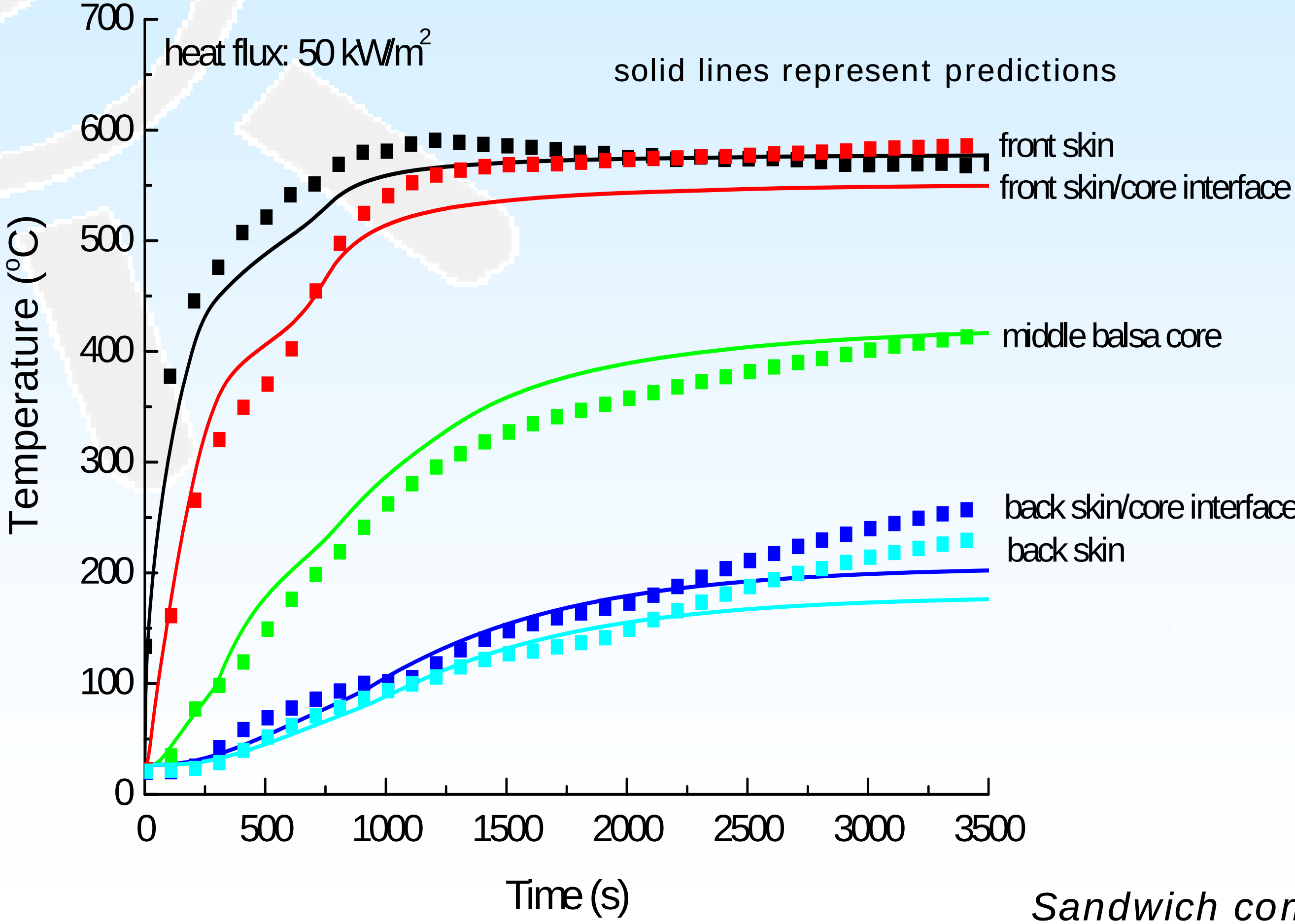


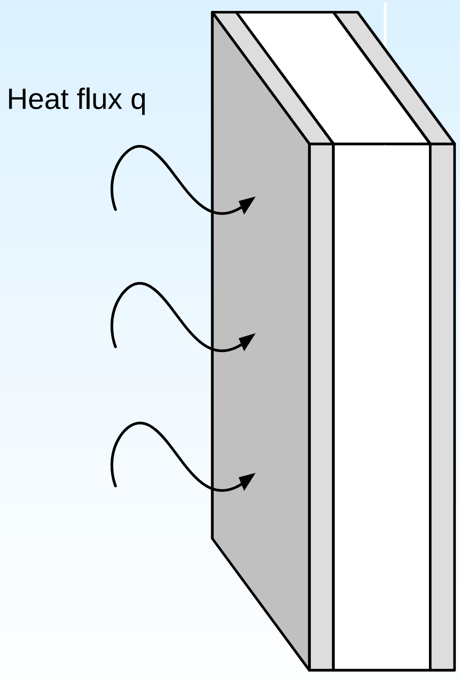


glass-vinyl ester @ 50kW/m^2 (600^{o}C)

Thermal Model

Thermal model works well for laminates & sandwich composites





Sandwich composite (with balsa core) @ 50kW/m² (600°C)

Decomposition Model

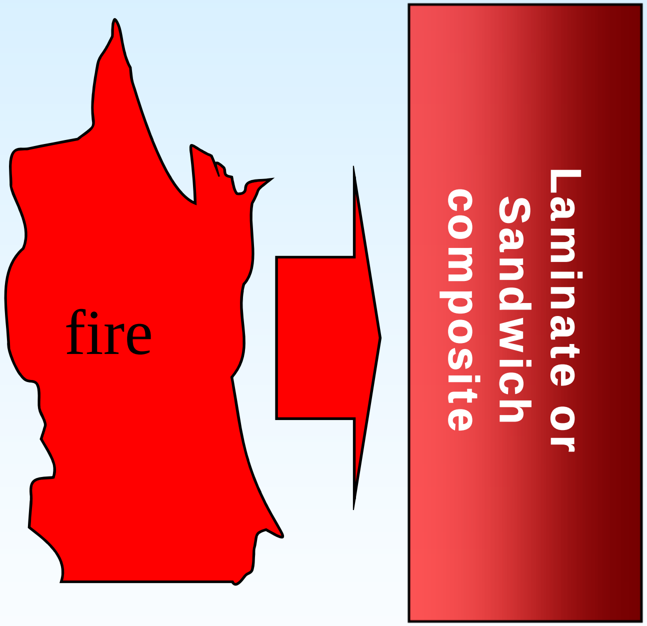
Thermal Analysis

Decomposition Analysis

Non-Uniform Property Changes

Bulk Mechanical Property Changes

Final Failure: Tension & Compression

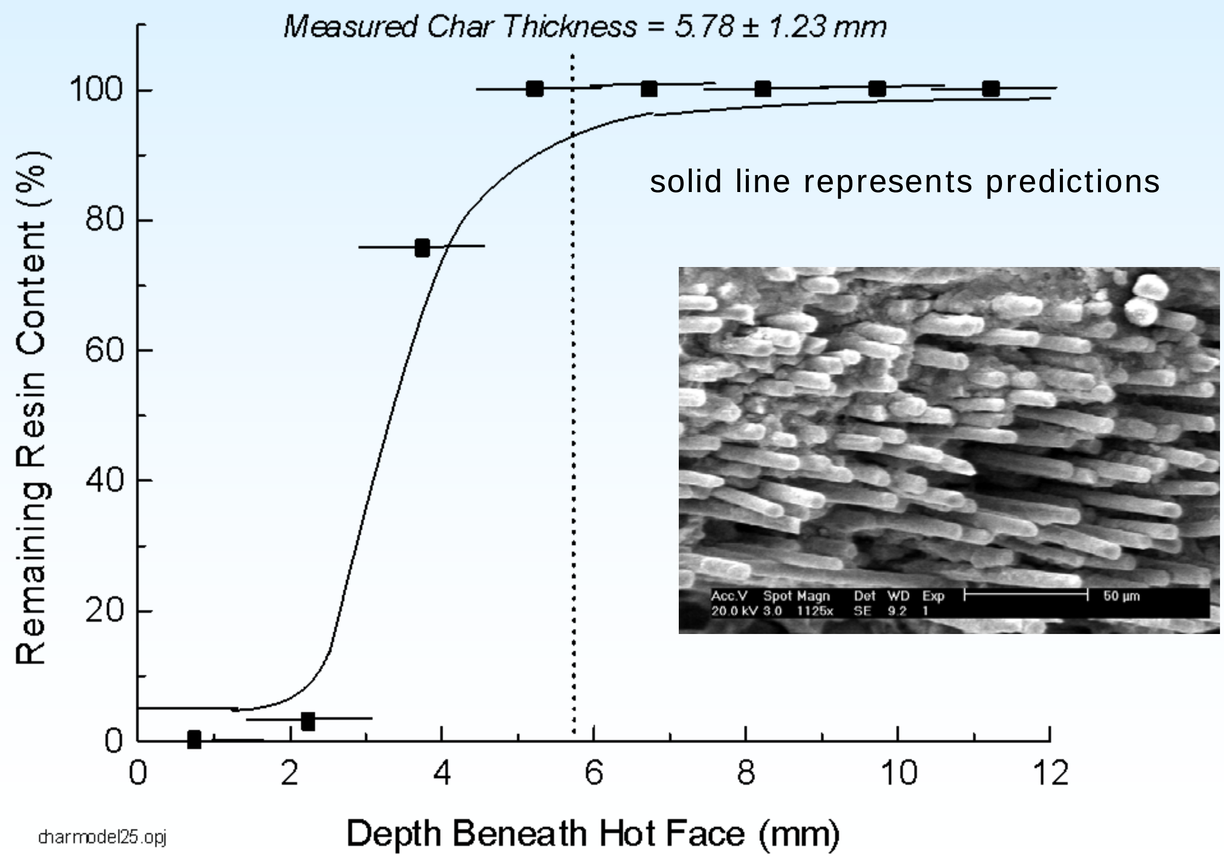


Decomposition Model

Decomposition of polymer matrix to char in through-thickness direction is calculated using model. No decomposition to fibre reinforcement assumed, although analysis is possible.

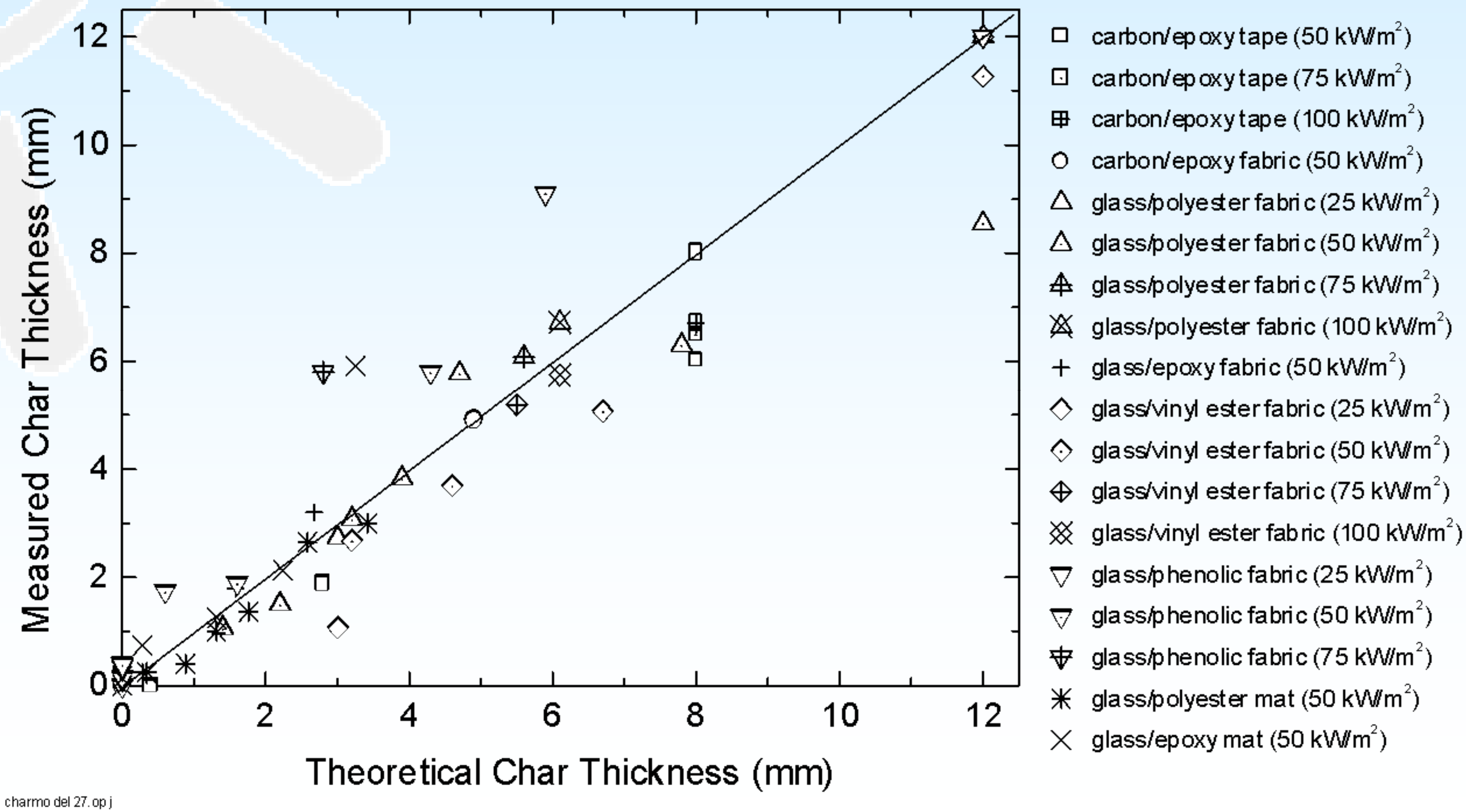
char

virgin laminate



Decomposition Model

Decomposition model works well for different composite systems under various heat flux conditions. Accurate prediction of decomposition (char) for many composites under range of heat flux conditions.

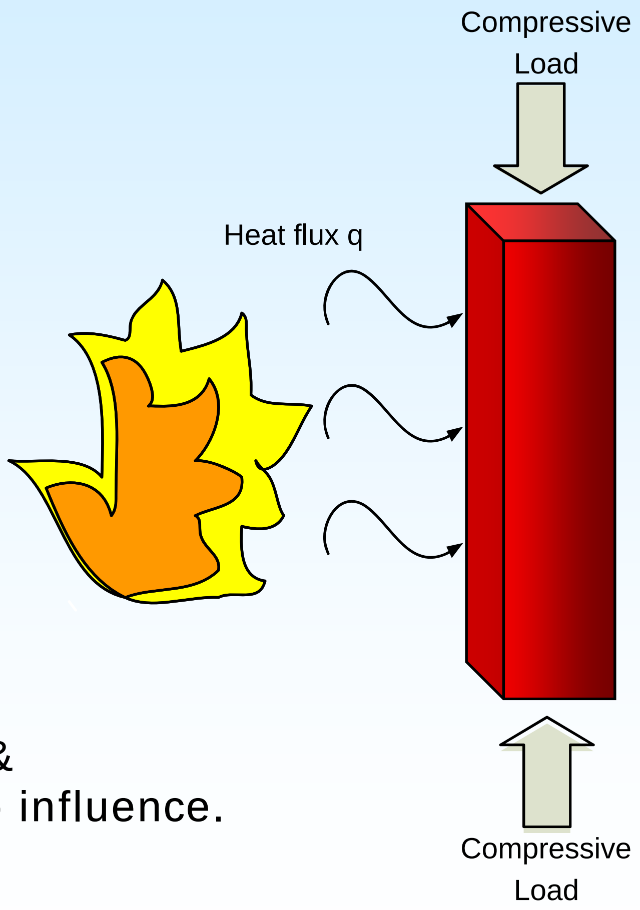


Compression Model

Compression properties of polymer laminates & sandwich composites exposed to fire.

Modelling based on the four step analysis:

1. Calculation of through-thickness temperature profile in composite
2. Calculation of temperature-dependent compression strength (matrix softening) at many points through the composite
3. Calculation of bulk strength of the composite
4. Prediction of compression failure.

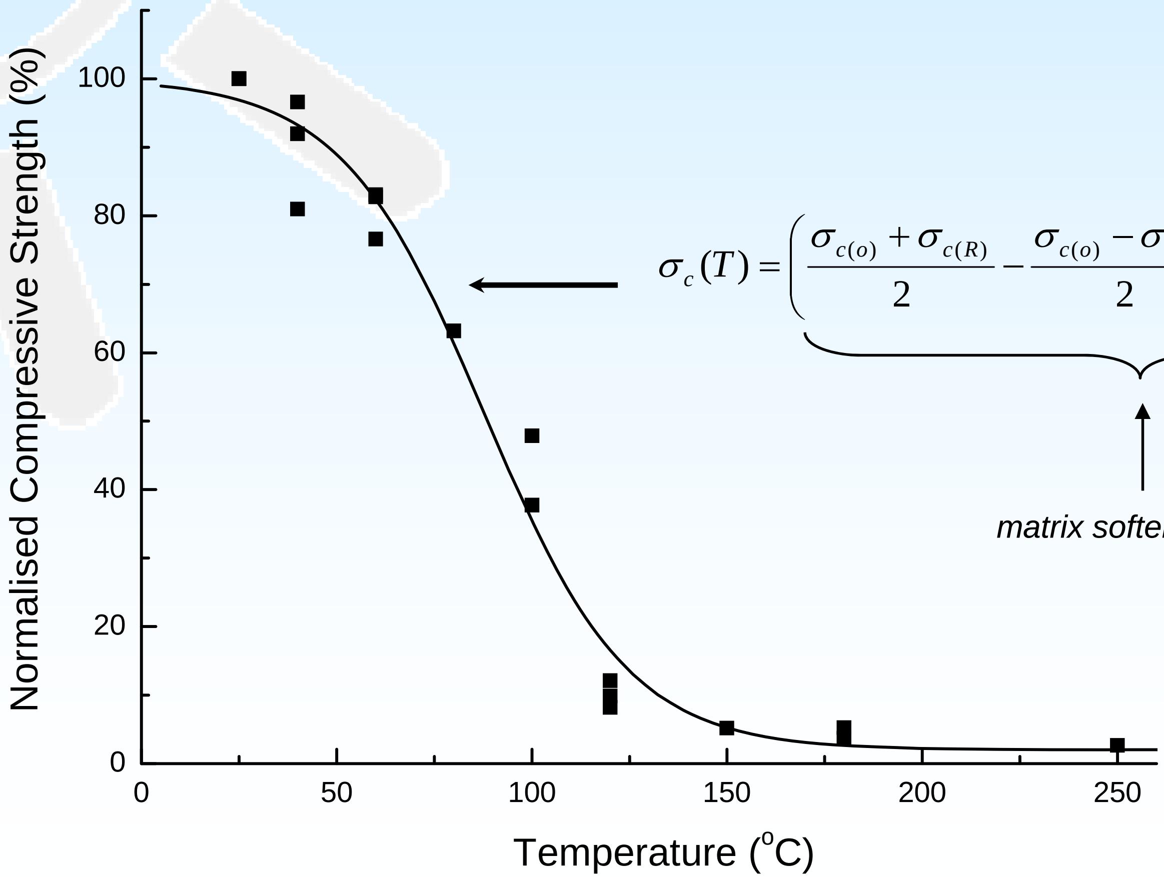


Assumed:

- Compression failure caused by thermal softening & decomposition of polymer matrix → fibres have no influence.
- Creep is not dominate in failure event.

Compression Model

Reduction in compression strength of composite is determined under isothermal conditions



$$\sigma_c(T) = \left(\frac{\sigma_{c(o)} + \sigma_{c(R)}}{2} - \frac{\sigma_{c(o)} - \sigma_{c(R)}}{2} \tanh(\Phi(T - T_k)) \right) R_{rc}(T)^n$$

matrix softening term

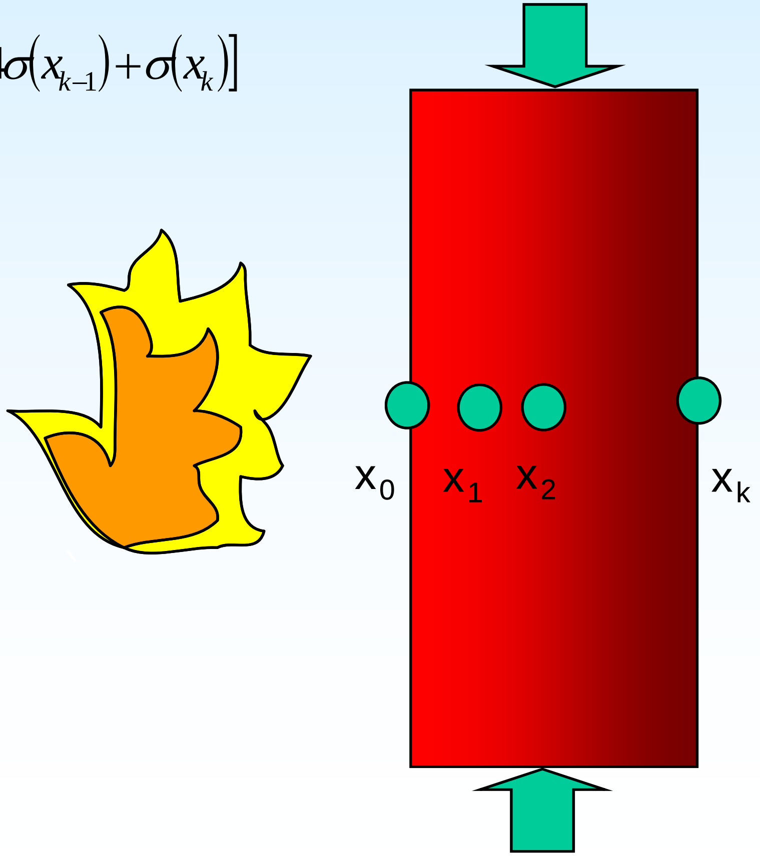
matrix decomposition term

Compression Model

"Smeared" approach to model compression strength of hot decomposing composite

$$\int_0^{t_c} \sigma(x)dx = \frac{t_c}{3m}\left[\sigma(x_0) + 4\sigma(x_1) + 2\sigma(x_2) + \ldots + 2\sigma(x_{k-2}) + 4\sigma(x_{k-1}) + \sigma(x_k)\right]$$

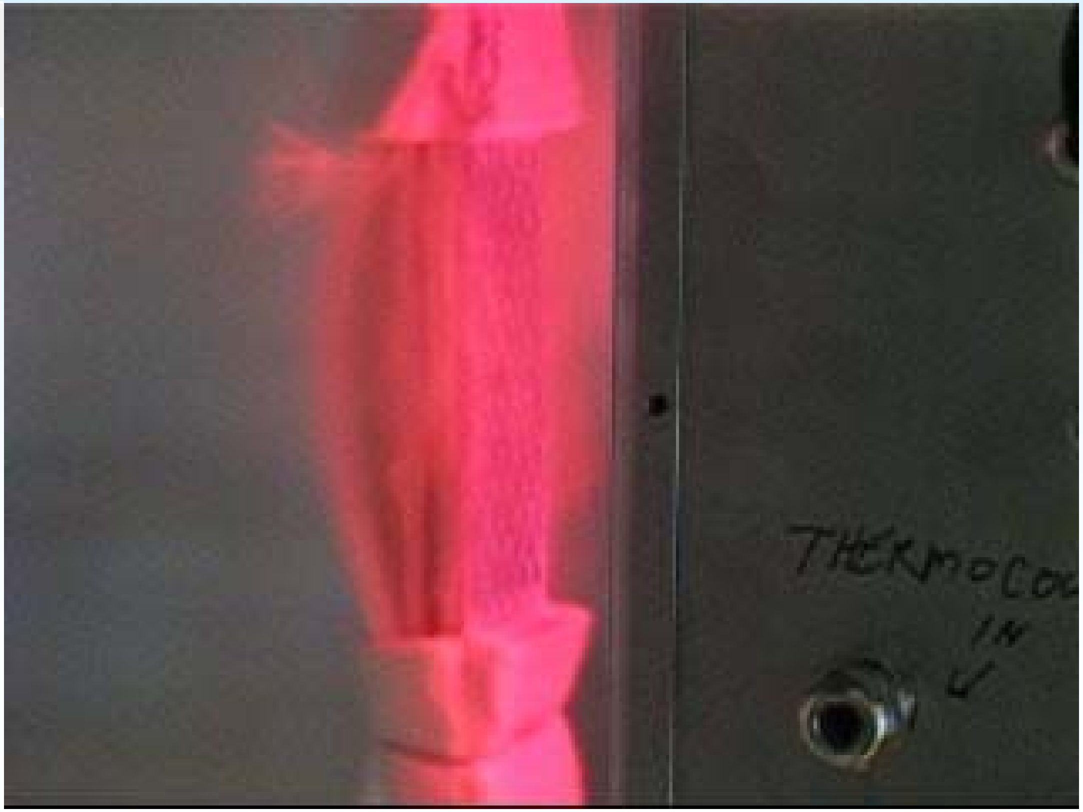
$$\sigma_{av} = \frac{1}{t_c}\int_0^{t_c} \sigma(x)dx$$



Compression Model

Experimental validation of compression model using fibreglass laminates & sandwich composites.

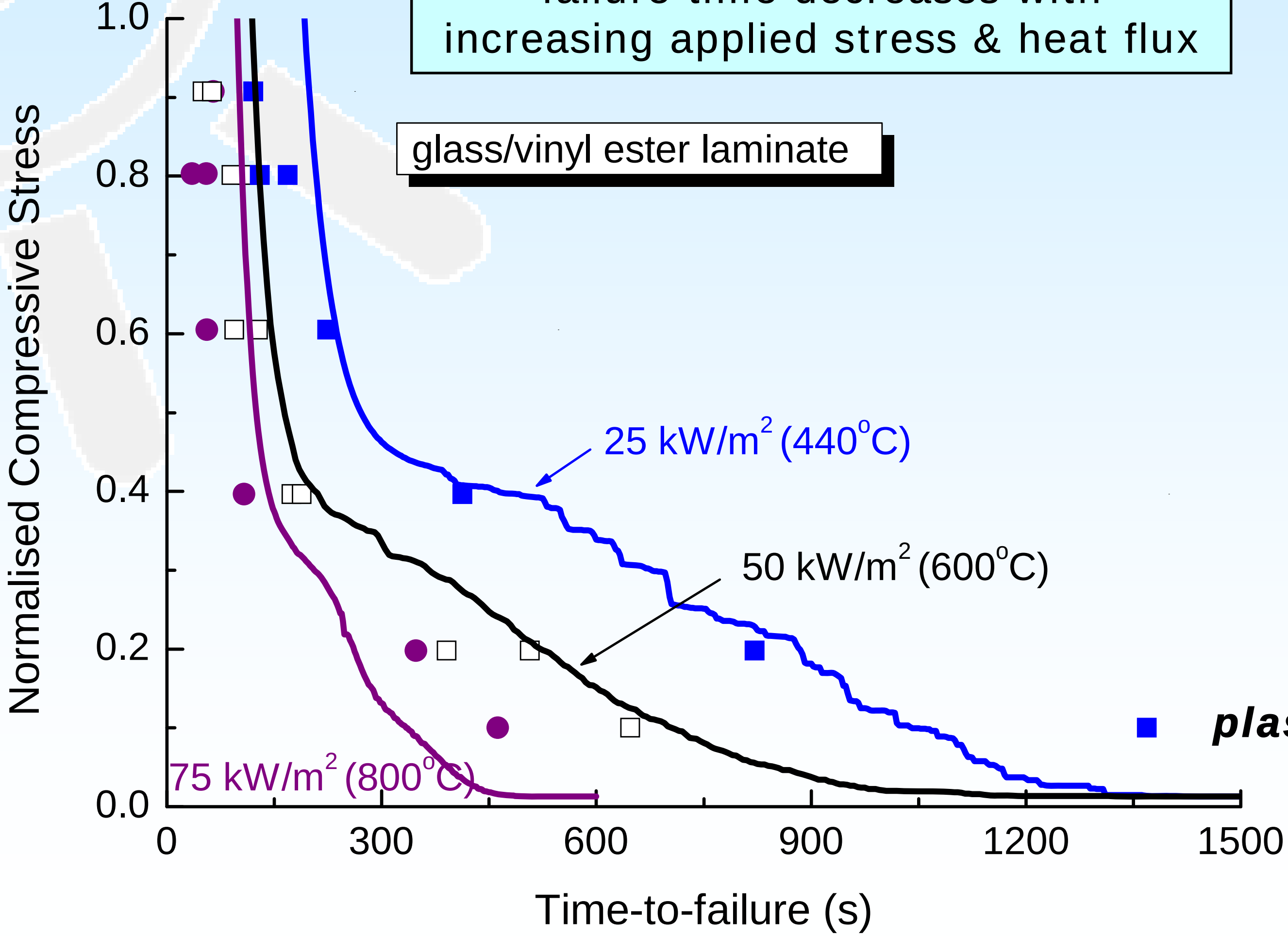
Research in progress using carbon fibre laminates.



Compression Model

Model validation for polymer laminates

failure time decreases with
increasing applied stress & heat flux

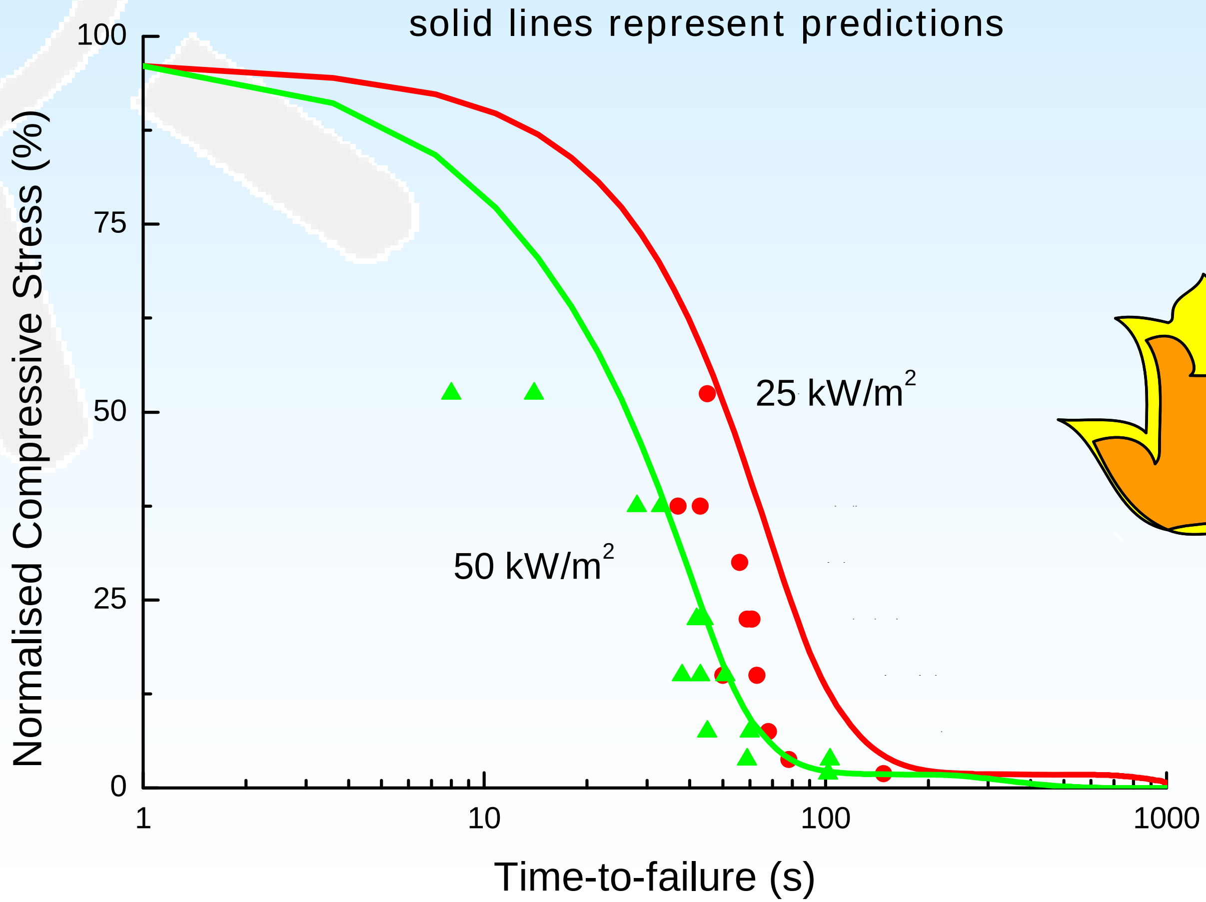


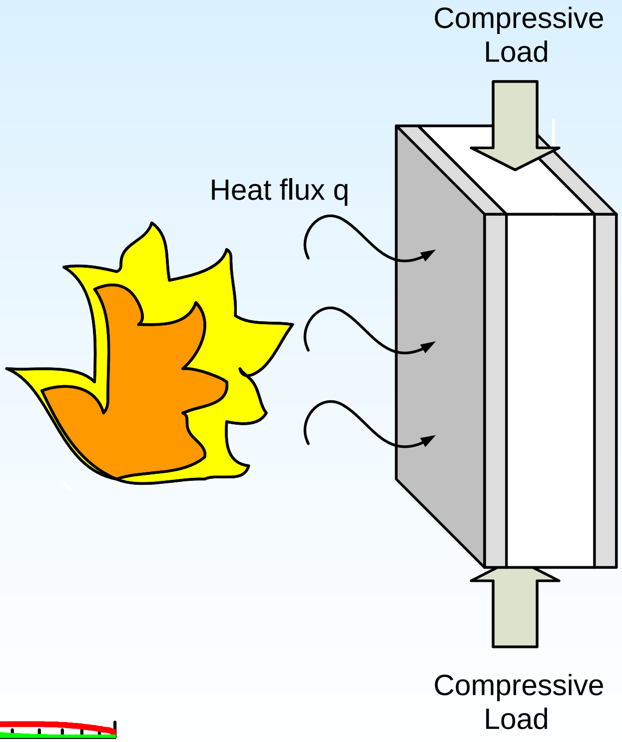
■ ***plastic kinking failure***

Compression Model

Model validation for sandwich composites.

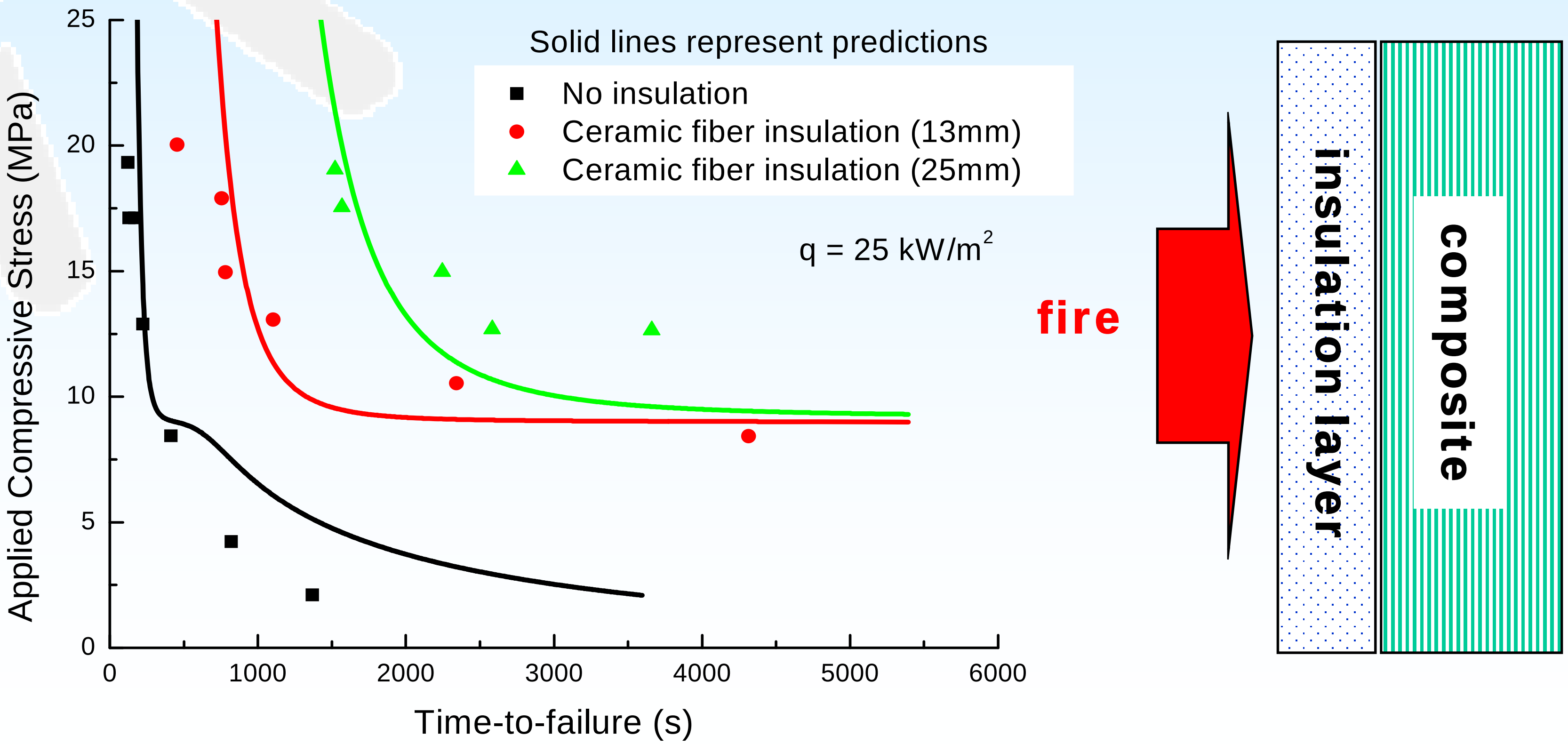
Poor agreement at low heat flux due to creep-dominated failure.





Compression Model

- Composites used in high fire risk applications are often protected with a thermal barrier material (eg. intumescent coating, ceramic fibre mat).
- Model can analyze composites with thermal barrier.

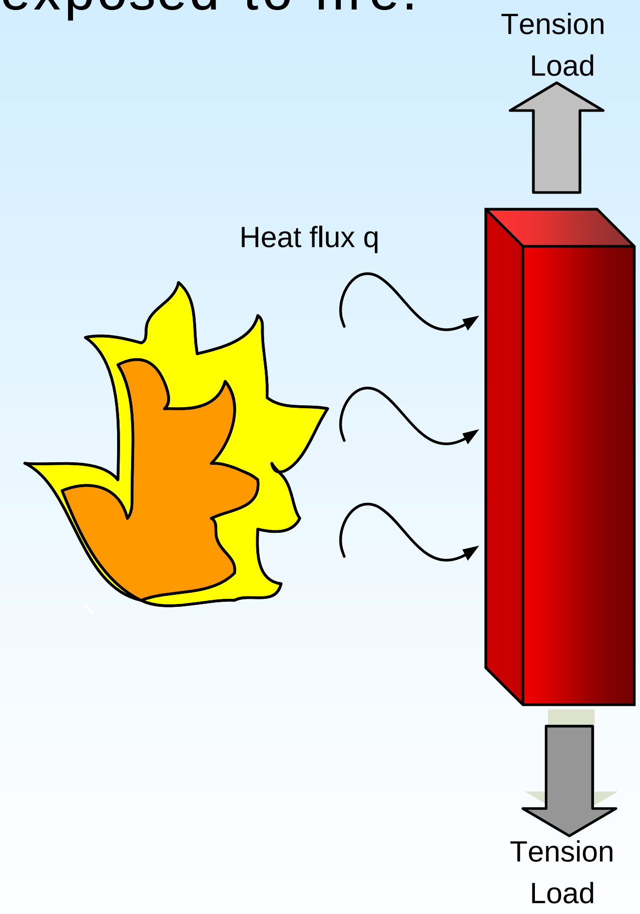


Tension Model

Tension properties of polymer laminates exposed to fire.

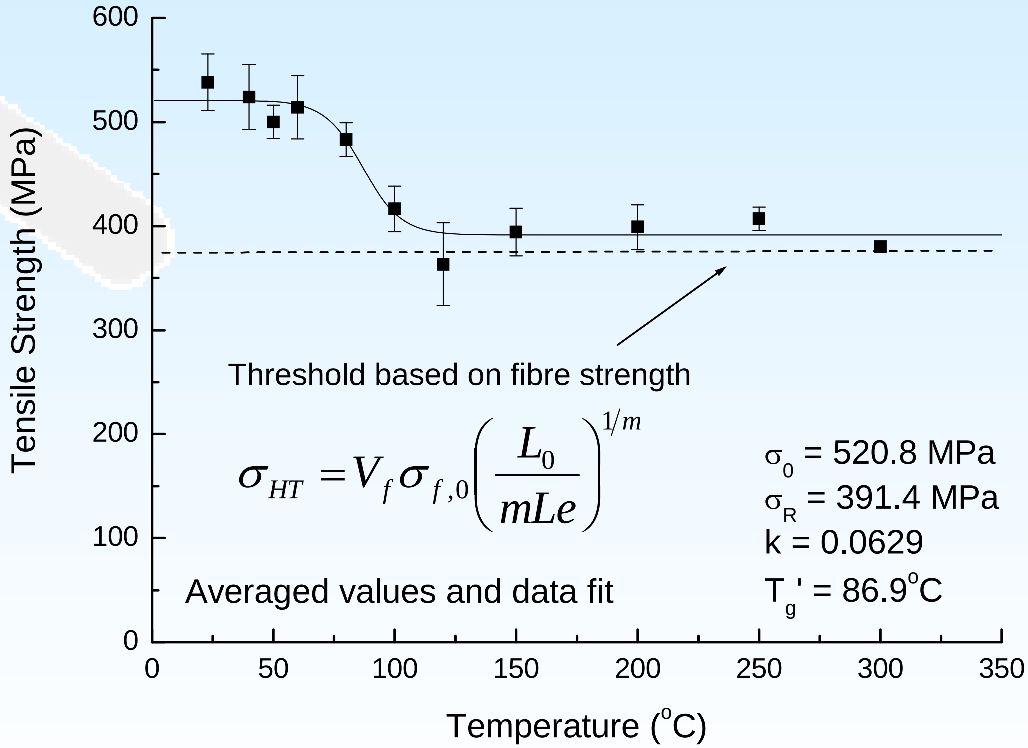
Modelling based on the five step analysis:

1. Calculation of through-thickness temperature profile in composite
2. Calculation of temperature-dependent tension strength of polymer matrix at many points through the composite
3. Calculation of temperature-time dependent strength of fibres at many points through the composite
4. Calculation of bulk tensile strength of the composite
5. Prediction of tensile failure.



Tension Model

Reduction in tension strength of composite is determined under isothermal conditions

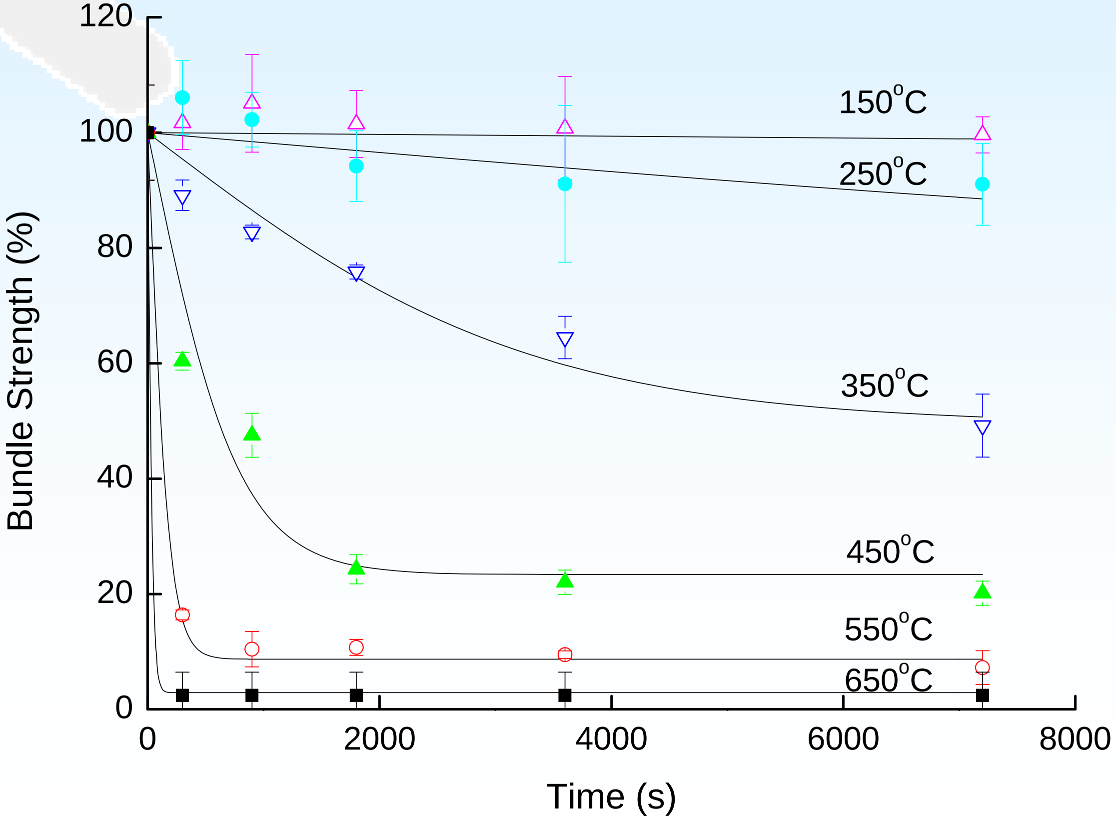


$$\sigma(T) = \frac{\sigma_{(0)} + \sigma_{(R)}}{2} - \frac{\sigma_{(0)} - \sigma_{(R)}}{2} \tanh\left(k\left(T - T_g^{'}\right)\right)$$

Tension Model

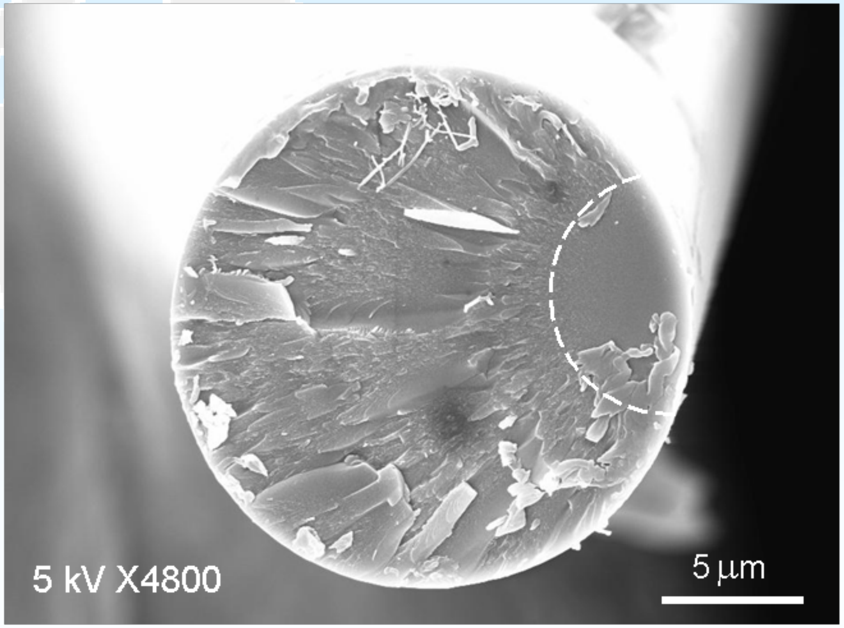
Reduction in tension strength of glass fibre (without matrix) is determined under isothermal conditions

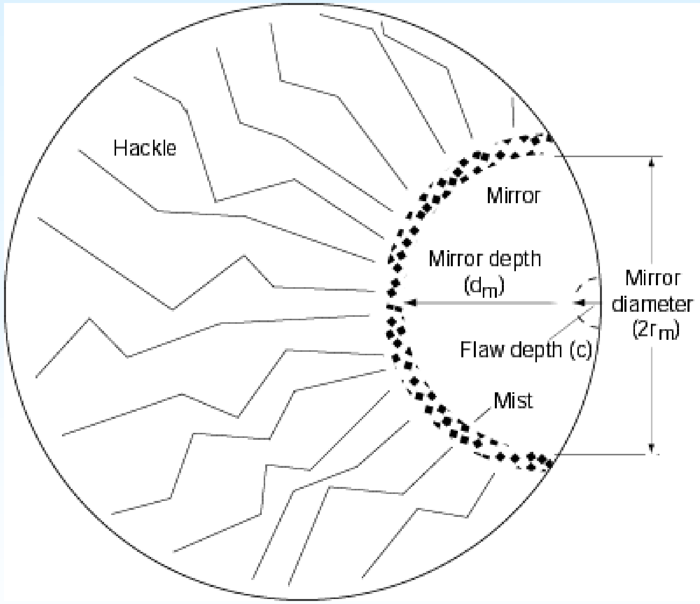
$$\sigma_{fb}(t,T) = \sigma_{fb(0)} - \sigma_{\text{loss}}(T)\tanh\left[k_{fb}(T)t\right]$$



Tension Model

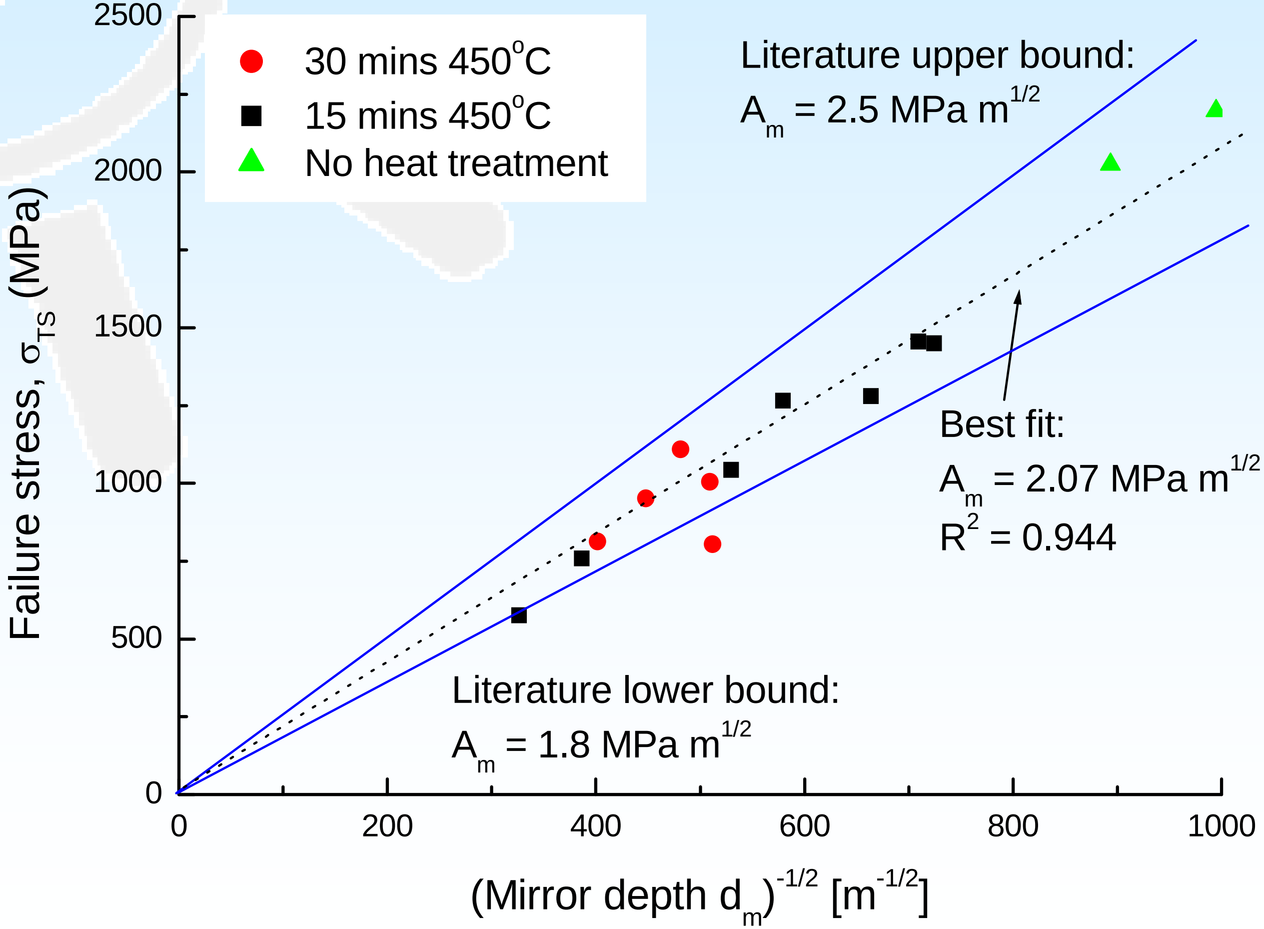
Investigated mechanism responsible for strength loss of glass fibres at high temperatures

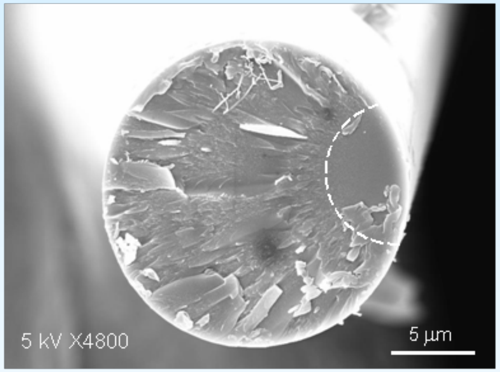


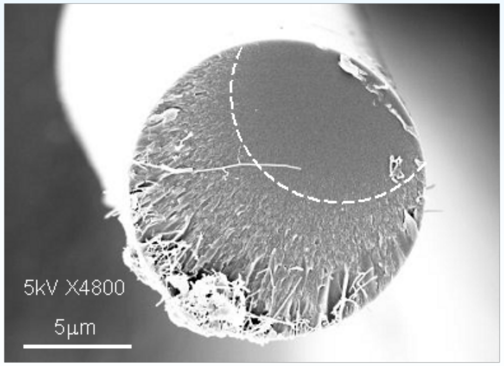


Tension Model

Glass fibre strength loss due to high temperature flaw growth







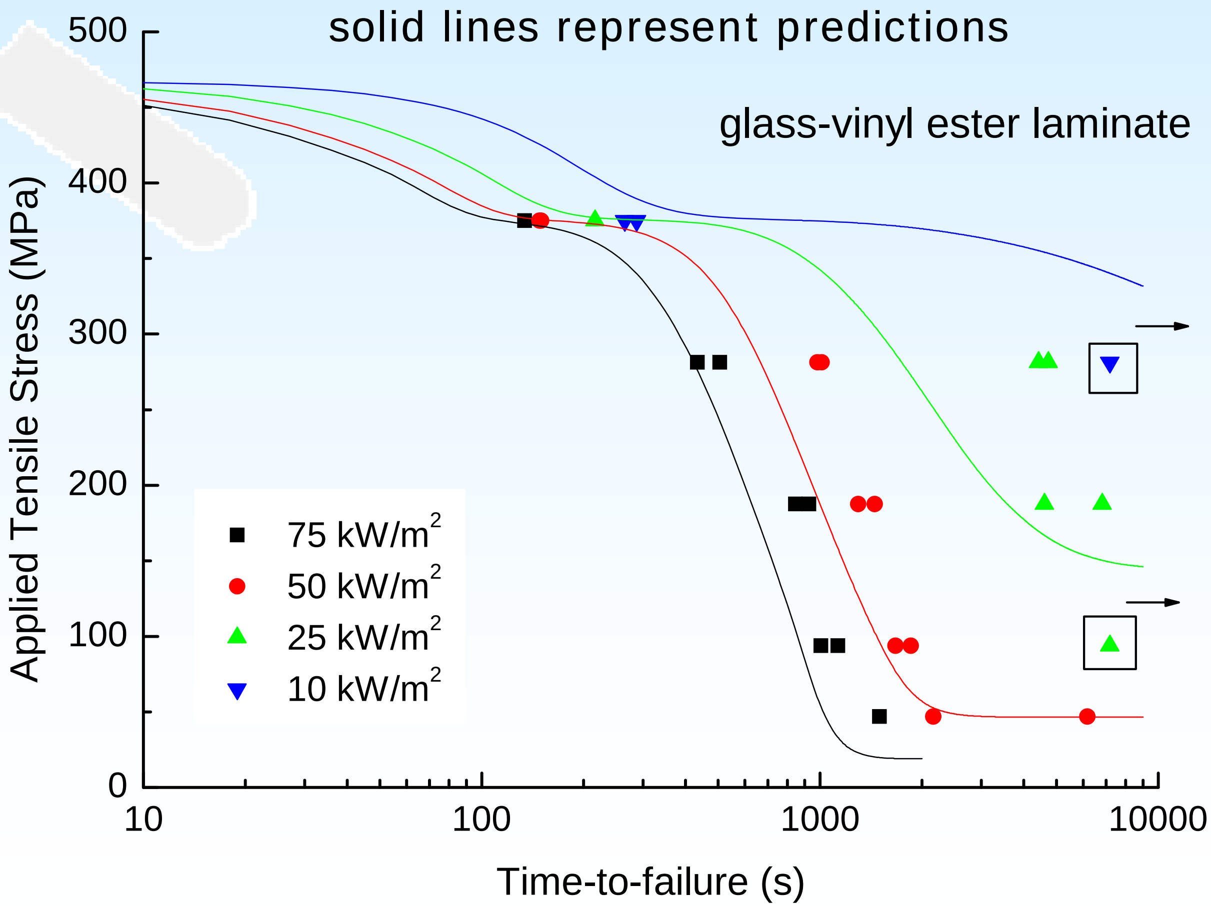
Tension Model

Experimental validation of tension model using fibreglass laminates

Tension Model

Experimental validation of tension model.

Failure can occur after complete matrix decomposition.



Post-Fire Models

Models developed to predict the residual stiffness & strength of polymer composites *following* fire exposure.

Models developed for

- tensile properties
- compression properties
- flexural properties

Two-layer model:

- decomposition (char)
- virgin laminate

Post-Fire Models

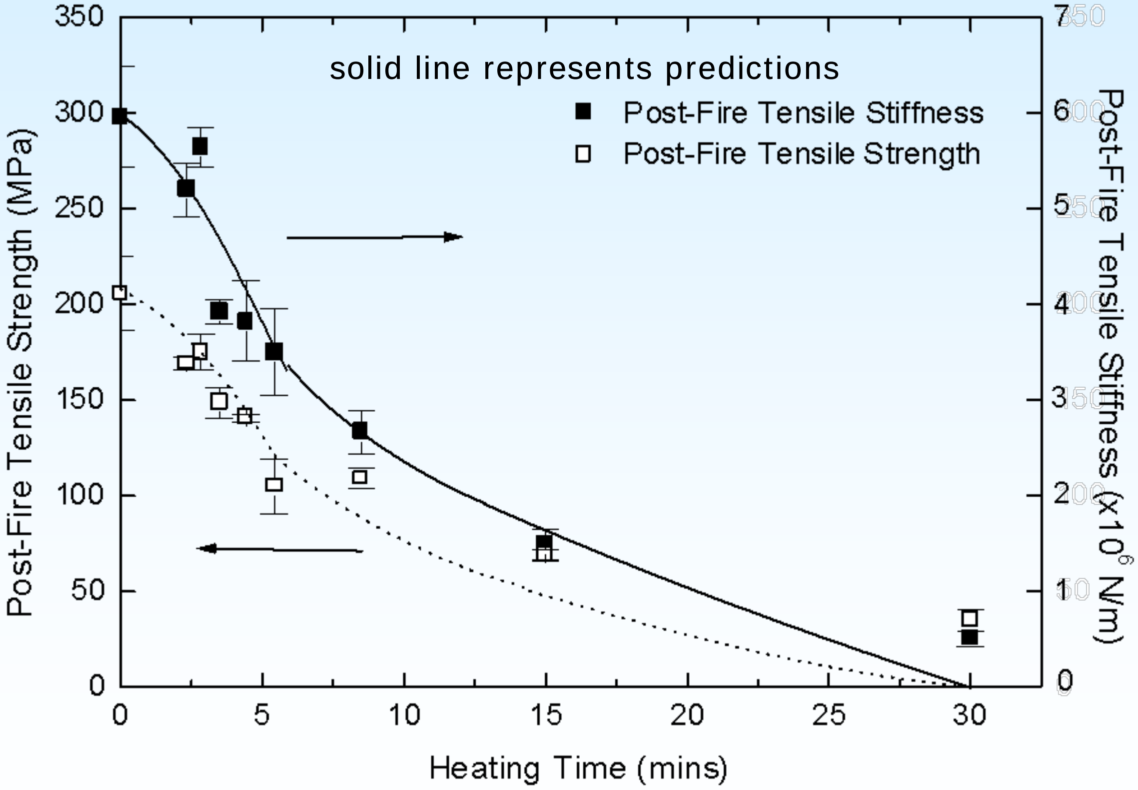
Example of models: post-fire tension stiffness & strength

tensile stiffness

$$S_t = \left(\frac{d - d_c}{d}\right).S_o + \left(\frac{d_c}{d}\right).S_c$$

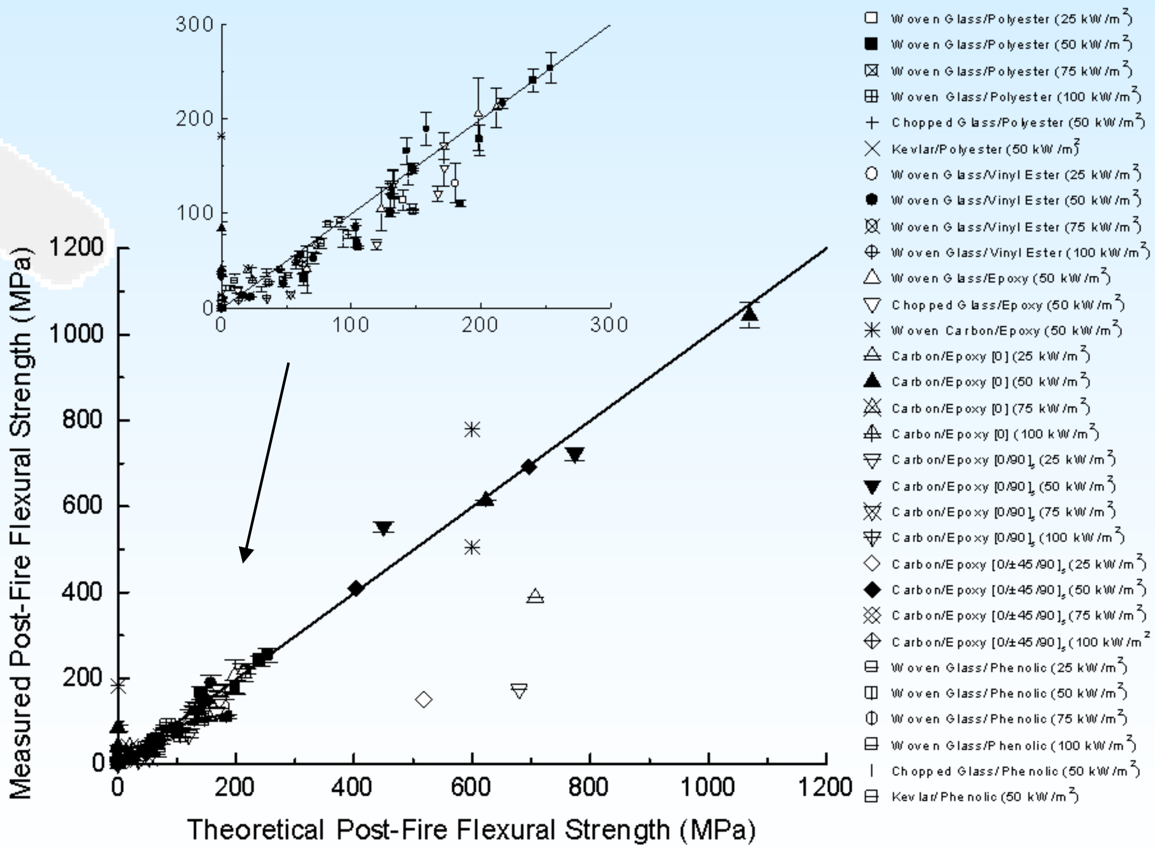
tensile strength

$$\sigma_t = \left(\frac{d - d_c}{d}\right).\sigma_{t(o)} + \left(\frac{d_c}{d}\right).\sigma_{t(c)}$$



Post-Fire Models

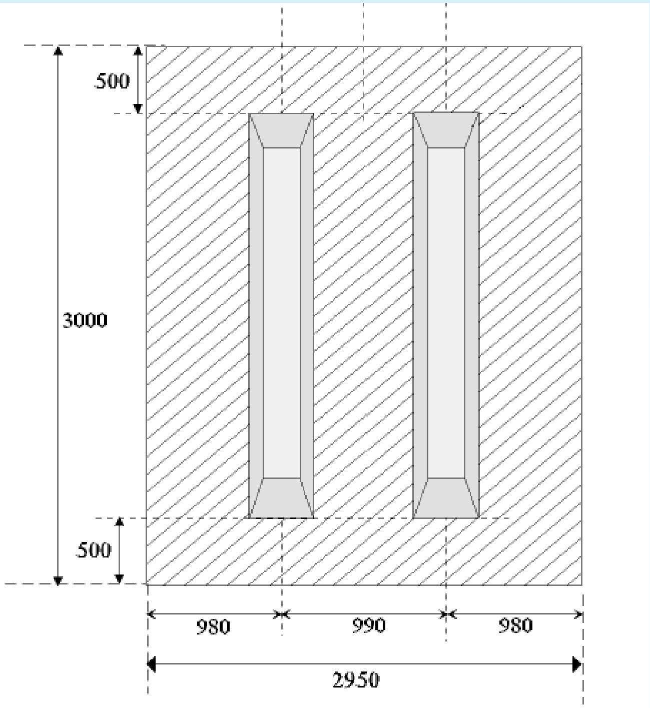
Example of models: post-fire flexural strength



$$P_f = \frac{8}{L^*}\left\{\frac{\sigma_{f(o)}.b}{3}.\frac{(d-d_n)^3+(d_n-d_c)^3}{(d-d_n)} + \frac{\sigma_{f(o)}.b}{3}.\frac{E_{f(c)}}{E_{f(o)}}.\frac{[d_n^3-(d_n-d_c)^3]}{(d-d_n)}\right\}$$

Future Research

- Development & validation of creep-based failure models for laminates & sandwich composites
- Large-scale fire test validation of models (1 x 1 m & 3 x 3 m panels)
- Validation using aerospace laminates & sandwich composites
- High temperature damage mechanisms of carbon fibres & carbon fibre composites
- Development of models for metal-fibre laminates (eg. GLARE)



Questions