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Modelling the tension and compression strengths of polymer laminates in fire

S. Feih [a,b], Z. Mathys [c], A.G. Gibson [d], A.P. Mouritz [a,b,*]

[a] *School of Aerospace, Mechanical and Manufacturing Engineering, Royal Melbourne Institute of Technology, GPO Box 2476V, Melbourne, Vic. 3001, Australia*
[b] *Cooperative Research Centre for Advanced Composite Structures Ltd (CRC-ACS), 506 Lorimer Street, Fishermans Bend, Vic. 3207, Australia*
[c] *Platform Sciences Laboratory, Defence Science and Technology Organisation, GPO Box 4331, Melbourne, Vic. 3001, Australia*
[d] *Centre for Composite Materials Engineering, Stephenson Building, University of Newcastle-upon-Tyne, United Kingdom*

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Abstract

Thermo-mechanical models are presented for predicting the time-to-failure of polymer laminates loaded in tension or compression and exposed to one-sided radiant heating by fire. Time-to-failure is defined as the time duration that a polymer laminate can support an externally applied load in a fire without failing. The models predict the temperature rise and through-thickness temperature profile in a hot decomposing laminate exposed to fire. Using this thermal data, mechanics-based models based on residual strength analysis are used to calculate the time-to-failure. A preliminary evaluation of the accuracy of the models is presented using failure times measured in fire-under-load tests on a woven glass/vinyl ester laminate. The model was evaluated at temperatures between ∼250 and 800 °C by testing the laminate at heat flux levels between 10 and 75 kW/m^2. It was found that the time-to-failure of the laminate decreased with increasing heat flux and increasing applied stress for both the compression and tension load conditions. The tests also revealed that the failure times were much shorter (by about one order of magnitude) when the laminate was loaded in compression. The models can predict the time-to-failure with good accuracy for both compression and tension loading for certain heat flux levels. However, because the models have only been evaluated for one type of laminate (woven glass/vinyl ester), further evaluation is necessary for other laminate systems. The paper also presents new experimental insights into the strengthening mechanisms of laminates at high temperature.

Keywords: A. Polymer-matrix composites (PMCs); A. Glass fibres; B. Thermomechanical properties; B. Modelling; Fire

1. Introduction

Polymer matrix composites have long been plagued by the problem of high flammability and poor fire resistance. This problem is a major concern when composite materials are used in applications where fire can occur, such as aircraft cabins, ships, offshore drilling platforms, submarines and rail carriages. Many types of polymer composites are highly flammable and pose a serious fire hazard due to the released heat, smoke and toxic fumes when they burn. Furthermore, thermal softening and pyrolysis of the matrix and softening of the fibre reinforcement causes composites to distort, weaken and eventually fail when supporting an external load.

A large amount of research has been performed to characterise the fire properties and reduce the flammability of composite materials [1–28], although less is known about the structural behaviour of composites in fire. Several studies have examined the effect of high temperature or fire on the load-bearing properties of polymer laminates and

* Corresponding author. Address: School of Aerospace, Mechanical and Manufacturing Engineering, Royal Melbourne Institute of Technology, GPO Box 2476V, Melbourne, Vic. 3001, Australia. Tel.: +61 3 9925 6269; fax: +61 3 9925 6003.
E-mail address: adrian.mouritz@rmit.edu.au (A.P. Mouritz).

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sandwich composites [29–34]. These studies have shown that thermal softening, creep and decomposition of the polymer matrix and softening of the fibre reinforcement degrade the tension properties whereas matrix softening and delamination cracking reduce the compression properties. Models have been developed to determine the effect of simultaneous loading and one-sided heating on the compression properties of polymer laminates [29–33]. Several models only consider the mechanical performance of laminates heated to a moderate temperature (typically below 300 °C), which is too low to cause ignition and burning of the polymer matrix. These models only consider the effects of thermal softening and creep on the mechanical properties. However, models able to predict the mechanical properties of burning composite materials in a hot fire are required. Gibson et al. [34] recently developed a thermo-mechanical model to predict the degradation of the mechanical properties of burning polymer laminates. The model can calculate the through-thickness temperature profile of a laminate exposed to one-sided heating by a fire. Using the temperature-dependent properties of the material, it is possible to calculate the reduction in the stiffness and strength using laminate theory. Gibson and colleagues showed that the model could predict the mechanical performance of fibreglass laminates under compression loading.

This paper presents two thermo-mechanical models for calculating the time-to-failure and strength properties of laminates in fire. Time-to-failure is defined as the time duration that a laminate can support an externally applied load in a fire without failing. One model predicts the time-to-failure of a hot decomposing laminate supporting a static compression load while the other model considers the static tension load condition. The models consider the situation of a non-flaming laminate exposed to fire, but do not consider the strength loss of the burning composite. A preliminary evaluation of the models is performed using time-to-failure values measured in fire-under-load tests performed on a woven glass/vinyl ester laminate. The tests involve measuring the time taken for the laminate to fail when supporting a constant compressive or tensile load when at the same time being subjected to one-side heating. The tests were performed at load levels between 10% and 90% of the ultimate strength of the laminate and at heat flux levels between 10 and 75 kW/m^2. A large amount of time-to-failure data is generated by the tests to evaluate the accuracy of the models for the glass/vinyl ester system.

2. Thermo-mechanical models

Two models are presented for calculating the time-to-failure of load-bearing polymer laminates when exposed to fire. The first model is used to predict the failure time of a laminate supporting an externally applied compressive load while the second model calculates the failure time for a laminate loaded in tension. Both models involve a two-step analysis approach that begins with a thermal analysis followed by a mechanical analysis. The thermal analysis determines the temperature profile through the laminate when exposed to one-sided heating. The mechanical analysis determines the variation in the strength properties through the laminate, which are dependent on the temperature profile. From this analysis, the reduction in the compression and tension strengths with increasing exposure time to a fire is calculated. The time-to-failure is determined by the time taken for the residual strength to decrease to the externally applied stress level, at which point failure must occur.

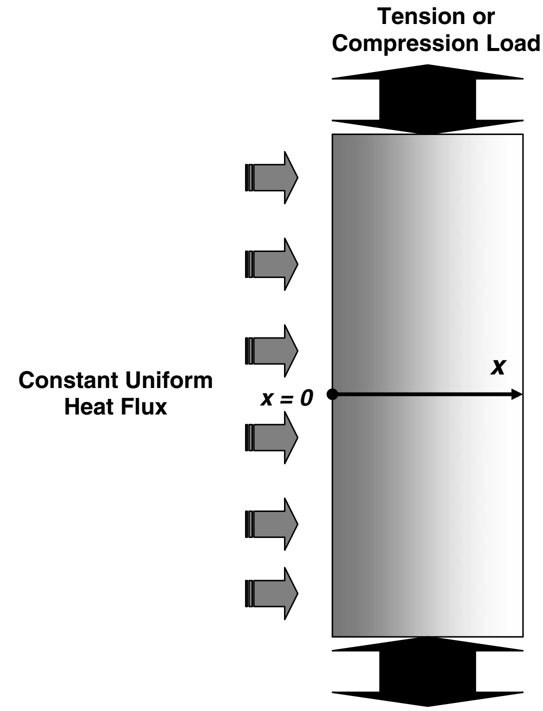

Fig. 1. Schematic of combined loading and one-sided heating of a laminate.

The models assume that one side of a laminate beam is evenly heated at a constant radiant heat flux, as shown schematically in Fig. 1. It is also assumed that the compression and tension loads are applied evenly across the laminate ends. The loads are applied in the axial (lengthwise) direction. Using these assumptions, the laminate can be treated as a one-dimensional system where the temperature and strength properties vary only in the through-thickness (x) direction.

Gibson et al. [35] formulated a model to calculate the thermal response of a hot decomposing laminate exposed to one-sided heating. The model, which is based on the analysis by Henderson et al. [36], can predict the temperature rise in a laminate. The model considers three important thermal processes on the temperature of a decomposing laminate. The first process is heat conduction from the fire/composite interface into the laminate, which causes the temperature the rise. The second process is heat generated or absorbed by decomposition of the polymer