



## Review of fire structural modelling of polymer composites

A.P. Mouritz<sup>a,\*</sup>, S. Feih<sup>a</sup>, E. Kandare<sup>a</sup>, Z. Mathys<sup>b</sup>, A.G. Gibson<sup>c</sup>, P.E. Des Jardin<sup>d</sup>, S.W. Case<sup>e</sup>, B.Y. Lattimer<sup>f</sup>

<sup>a</sup> School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, GPO Box 2476V, Melbourne, Vic., 3001, Australia

<sup>b</sup> Defence Science and Technology Organisation, GPO Box 4331, Melbourne, Vic., 3001, Australia

<sup>c</sup> Centre for Composite Materials Engineering, University of Newcastle-upon-Tyne, Newcastle NE1 7RU, England, United Kingdom

<sup>d</sup> Department of Mechanical and Aerospace Engineering, University of Buffalo, The State University of New York, Buffalo, NY 14260-4400, USA

<sup>e</sup> Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

<sup>f</sup> Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

### ARTICLE INFO

#### Article history:

Received 9 June 2009

Received in revised form 31 August 2009

Accepted 3 September 2009

#### Keywords:

A. Polymer matrix composites

B. Thermomechanical

B. Mechanical properties

C. Analytical modelling

Fire

### ABSTRACT

This paper presents a critical review of research progress in modelling the structural response of polymer matrix composites exposed to fire. Models for analysing the thermal, chemical, physical, and failure processes that control the structural responses of laminates and sandwich composite materials in fire are reviewed. Models for calculating the residual structural properties of composites following fire are also described. Progress towards validation of the models by experimental characterisation of the structural properties of composites during and following fire is assessed. Deficiencies in the fire structural models are identified in the paper, which provide the focus for future research in the field.

© 2009 Elsevier Ltd. All rights reserved.

### 1. Introduction

This paper presents a critical review of progress in the structural analysis and modelling of fibre–polymer composite materials in fire. Fire performance is one of the most significant factors affecting the wider use of composites in engineering structures [e.g. 1–5]. Unlike other structural materials such as steel, aluminium alloy and reinforced concrete, composites are reactive at high temperature due to the organic matrix and (when present) organic fibres (e.g. aramid, polyethylene). The types of composites often used in structures, such as glass–polyester, glass–vinyl ester, carbon–epoxy and carbon–thermoplastic materials, decompose when exposed to high temperature fire (typically above several 100°C), with the release of heat, smoke and fumes. The fire reaction behaviour of structural composite materials have been thoroughly characterised, and a large database of information is available on their time-to-ignition, heat release rate, limiting oxygen index, flame spread, smoke density and smoke toxicity properties [1,6–25]. There has also been progress in the development of models to calculate certain fire reaction properties, such as ignition time and heat release rate [23–27].

The major progress in the modelling and measurement of the fire reaction properties of composite materials has, until recently, not been matched by advances in the analysis of their structural

behaviour in fire. Understanding the fire structural performance is a critical safety issue because the loss in stiffness, strength and creep resistance can cause composite structures to distort and collapse; possibly resulting in injury and death. While some progress has been made in developing thermal models for steel structures for use in computation fluid dynamic models of fire [28,29], much less is known about composite structures. Composites with high flammability and low fire resistance are being used increasingly in structural applications where fire is an ever present risk, such as aircraft, ships and offshore oil drilling platforms. The fire structural response is arguably as important to safety as the fire reaction behaviour that has been more widely studied. Therefore, modelling the fire structural response of composites is essential to assessing their survivability and safety.

Until recently, models to analyse the structural behaviour of composites in fire were not available. Instead, the conventional approach to assess the structural response has been to perform fire tests on composite components that are representative of the structural application, such as bulkhead panels for ships or fuselage sections for aircraft [e.g. 30–32]. These tests provide information on the mechanical integrity and burn-through resistance of the structural design for the specific fire test condition. However, the tests are expensive, complicated to perform, and only provide information relevant to the fire test condition. It is not possible to extrapolate the information from these tests to predict the structural behaviour of composite components in other fire scenarios.

\* Corresponding author. Tel.: +61 3 9925 6269; fax: +61 3 9925 6108.

E-mail address: [adrian.mouritz@rmit.edu.au](mailto:adrian.mouritz@rmit.edu.au) (A.P. Mouritz).

## Nomenclature

$A$	pre-exponential factor for decomposition reaction of polymer matrix	$P_f$	post-fire flexural failure load of composite
$b$	width of composite beam	$P_o$	mechanical property of composite at room temperature
$C$	boundary condition constant	$P_R$	fully-relaxed property of composite
$C_p$	specific heat capacity of composite	$P_t$	post-fire tensile failure load of composite
$C_{p(c)}$	specific heat capacity of decomposed (char) composite	$P_{t(char)}$	tensile failure load of decomposed (char) composite
$C_{p(g)}$	specific heat capacity of gas	$P_{t(o)}$	tensile failure load of virgin composite
$C_{p(v)}$	specific heat capacity of virgin composite	$p$	internal gas pressure
$C_{pj(c)}$	curve-fit coefficients for the specific heat capacity of decomposed (char) composite ( $j = 1, 2, \dots$ )	$p_o$	internal ambient pressure
$C_{pj(v)}$	curve-fit coefficients for the specific heat capacity of virgin composite ( $j = 1, 2, \dots$ )	$S$	compliance of composite
$d$	total thickness of composite	$Q_p$	decomposition energy of polymer matrix
$d_c$	thickness of decomposed (char) layer	$q''_{rad}$	radiant incident heat flux
$d_n$	neutral axis of composite	$q''_{s,L}$	heat flux at cold surface
$E$	activation energy for decomposition reaction of polymer matrix	$q''_{s,o}$	heat flux at fire-exposed surface
$E_c$	post-fire compression modulus of composite	$R$	universal gas constant
$E_{c(char)}$	compression modulus of decomposed (char) composite	$R^n$	residual resin content
$E_{c(o)}$	compression modulus of virgin composite	$T$	temperature
$E_f$	post-fire flexural modulus of composite	$T_{av}$	average temperature over a fixed distance
$E_{f(char)}$	flexural modulus of decomposed (char) composite	$T_g$	glass transition temperature
$E_{f(o)}$	flexural modulus of virgin composite	$T_s$	fire-exposed surface temperature
$E_t$	post-fire tensile modulus of composite	$T_\infty$	reference temperature
$E_{t(o)}$	tensile modulus of virgin composite	$t$	time
$E_{t(char)}$	tensile modulus of decomposed (char) composite	$t_{eff}$	effective heating time
$F$	mass fraction of virgin material in decomposing composite	$V_c$	volume fraction of decomposed (char) material in the composite
$G_{12}$	in-plane shear modulus of composite	$V_m$	volume fraction of polymer matrix
$h_c$	enthalpy of the composite	$v$	gas velocity
$h_{conv}$	enthalpy of convective heat	$x$	distance in through-thickness direction below the fire-exposed surface
$h_g$	enthalpy of the volatile gas	$\alpha_c$	thermal expansion coefficient of decomposed (char) composite
$k_{j(v)}$	curve-fit coefficients for the thermal conductivity of the virgin laminate ( $j = 1, 2$ )	$\alpha_v$	thermal expansion coefficient of virgin composite material
$k_{j(c)}$	curve-fit coefficients for the thermal conductivity of the char material ( $j = 1, 2, 3, 4$ )	$\chi$	number of points in through-thickness direction
$k_\perp$	through-thickness thermal conductivity	$\Delta A_c$	cross-sectional area
$k^{cr}$	thermal conductivity of delamination	$\Delta x$	thermal expansion in the through-thickness direction
$k_v$	thermal conductivity of virgin composite	$\varepsilon_s$	emissivity of the composite
$k_c$	thermal conductivity of decomposed (char) composite	$\varepsilon$	strain
$L_c$	unsupported length of composite beam	$\varepsilon_T$	strain generated by external loading
$L_f$	bending support span length	$\xi$	empirical decomposition coefficient
$MC$	moisture content	$\xi_i^*$	curve-fit coefficient for property-temperature ( $i = 1, 2, \dots$ )
$m$	instantaneous mass fraction of polymer matrix during decomposition	$\eta$	heating rate
$m_d$	mass fraction of decomposed polymer matrix	$\varphi_{cr}$	volume fraction of delamination cracks
$m_o$	initial mass fraction of polymer matrix prior to decomposition	$\varphi_s$	volume fraction of solid material
$m_f$	final mass fraction of polymer matrix following decomposition	$\Phi$	porosity
$m_g$	mass flux of volatiles	$\bar{\phi}$	average angle of load-bearing fibres
$n$	order of the decomposition reaction of the polymer matrix	$\rho$	instantaneous density of composite
$n_\lambda$	empirical constant	$\rho_v$	density of virgin composite
$n^*$	kink empirical constant	$\rho_c$	density of decomposed (char) composite
$P$	mechanical property of composite at elevated temperature	$\sigma$	stress
$P_c$	post-fire compression buckling failure load of composite	$\sigma^*$	Stefan-Boltzmann constant
$P_{c(char)}$	compression failure load of decomposed (char) composite	$\sigma_{fb(o)}$	tensile strength of glass fibre bundle at room temperature
$P_{c(o)}$	compression failure load of virgin composite	$\sigma_{f(o)}$	flexural strength of virgin composite
		$\sigma_c$	compression kink stress
		$\sigma_{loss}$	steady-state strength of the fibre bundle
		$\tau$	shear stress
		$\gamma_y$	shear yield strain

The key challenge to the modelling of composites in fire is the complexity of the thermal, chemical, physical, and failure processes which control the structural behaviour. A summary of the fire processes in polymer laminates is shown in Fig. 1, and are briefly described as follows:

- **Thermal processes.** This involves heat conduction from the fire into and then through the composite; heat generated or absorbed from decomposition (pyrolysis) of the polymer matrix, organic fibres and organic core material (for sandwich materials); convective heat loss from the egress of hot reaction gases

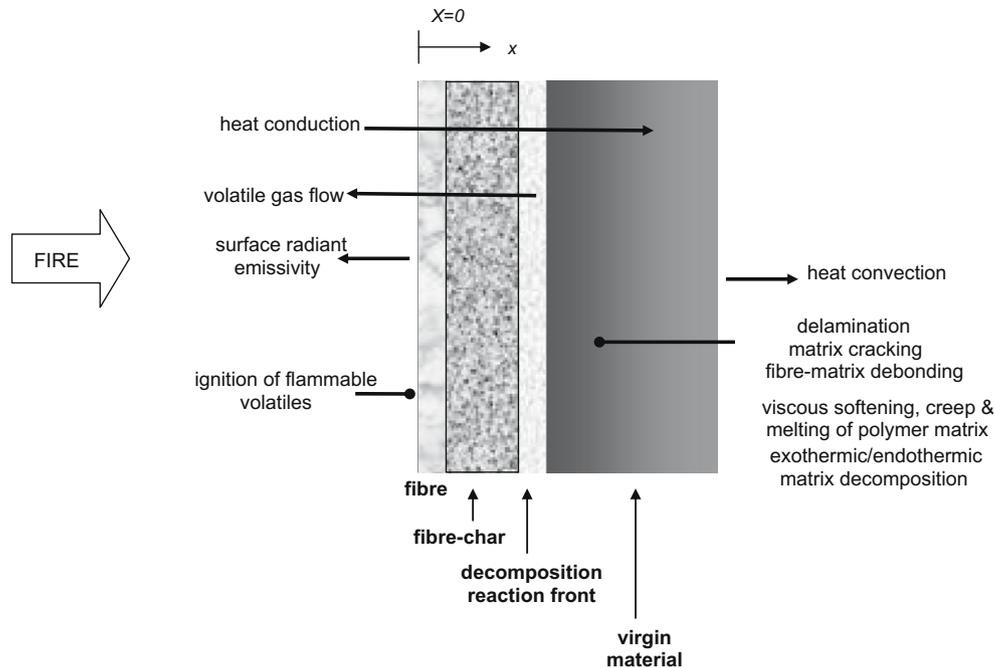


Fig. 1. Schematic of the reaction processes in the through-thickness direction of a hot, decomposing polymer composite during fire exposure.

and moisture vapours from the composite into the fire; heat generated through char or fibre oxidation; and heat generated by the ignition of flammable reaction gases at the composite–fire boundary.

- *Chemical processes (including phase transformations).* This involves viscous softening, melting, decomposition and volatilisation of the polymer matrix, organic fibres and core material; formation, growth and oxidation of char; oxidation of carbon fibres; and char–fibre reactions.
- *Physical processes.* This involves thermal expansion and contraction; thermally-induced strains; internal pressure build-up due to the formation of volatile gases and vaporisation of moisture; formation of gas-filled pores; matrix cracking; fibre–matrix interfacial debonding; delamination damage; surface ablation; and softening, melting and fusion of fibres.
- *Failure processes.* The failure mode depends on the temperature, heat flux and duration of the fire; magnitude and type of load (e.g. tension, compression, bending, torsion); and geometry of the structure.

The challenge to modelling the structural response of composites in fire is the accurate analysis and representation of these many processes. The analysis is further complicated because many of the processes do not occur in isolation from each other. Understanding these processes and how they interact is essential to analysing the fire structural behaviour.

The capabilities offered by being able to analyse the fire structural response underpin the need to develop models that are robust and mechanistically accurate. Models offer the capability for the rapid, low-cost assessment of the fire performance and survivability of existing and new design options for composite structures. The models reduce (but do not totally eliminate) the need to conduct fire structural tests. The models can also be used to further our understanding of the fire behaviour of traditional polymer composites and in the development of new materials with improved fire structural survivability.

Major advances have recently been made towards modelling the structural response of composites in fire. Thermal–mechanical

models have been developed to predict the temperature, decomposition, softening and failure of laminates and sandwich composites [33–79]. Models to calculate the post-fire properties have also been developed [72–90]. In addition, there has been important progress towards the validation of models with experimental fire structural tests, which includes the development of low-cost test procedures.

This paper presents an overview of the research progress into the structural modelling of laminates and sandwich composites in fire. The research has concentrated on laminates reinforced with non-combustible fibres (e.g. glass). Less research has been performed on laminates with reactive fibres and on sandwich materials. The paper describes models for calculating the temperature, decomposition, phase changes, damage, mechanical properties, and failure of composites in fire. The paper also describes the deficiencies in the models and identifies topics that require further modelling and analysis.

This paper is presented in sections which deal separately with the different processes that control the fire structural response of composites. There are separate sections on the thermal, decomposition, damage, softening, and failure modelling of composites. The processes are divided into these sections for convenience, but for modelling the processes are interdependent and do not occur in isolation from each other. Therefore, the complete approach to modelling involves the concurrent analysis of all the processes until final failure of the composite structure in fire.

## 2. Thermal modelling of composites in fire

### 2.1. Thermal analysis

Thermal modelling involves calculating the temperature distribution through the composite when subjected to one-sided heating by fire. Accurate modelling of heat transfer through the composite is the critical first step in fire structural analysis. Thermal modelling is also essential in the analysis of decomposition and damage to the material in fire. The thermal analysis of composites in fire is complicated because the heat transfer is controlled

by a multitude of temperature-dependent processes which are summarised in Table 1. The approximate temperatures over which these processes occur in a fibreglass laminate are shown in Fig. 2.

Thermal analysis of composites in fire is based largely on theoretical studies performed since the mid-1940s on the fire behaviour of wood [91–96]. Numerous studies – most notably by Kung [93], Kansa et al. [95] and Fredlund [96] – developed thermal-chemical models that analyse the processes of transient heat conduction, pyrolysis, convection flow of volatile gases, and volatile combustion at or near the fire exposed wood surface. These models have been adapted for composites in fire by Henderson and colleagues [97–102], Sullivan and Salamon [103–106], Springer and colleagues [107–109], Dimitrienko [110,111], Milke and Vizzini [112], and Gibson et al. [113]. The models all have the capability to calculate the temperature distribution through a composite exposed to fire, but differ in the processes that are considered in the analysis. The processes included in the various models are indicated in Table 1.

A common feature of many thermal modelling approaches is the decoupling of the fire from the composite. The initiation and growth of fire is not considered in the analysis. Furthermore, the interaction of the fire and composite surface is not analysed, including the effects of convective heat flow due to flame turbulence and the heat generated by the ignition of combustible gases released from the decomposing composite. Instead, most models ignore the dynamics of the fire event, and simply assume the composite surface is heated under controlled heat flux or temperature conditions. Desjardin and colleagues [47–51] recently developed a coupled fluid–structure modelling approach to analyse heat transfer from the flame into the material. Computational fluid mechanics (CFD) is used to analyse the flow dynamics and temperatures of the flame over the composite surface. A grid embedding technique is used to couple the flame to the solid surface. The thermal models for composites are then used to analyse heat flow from the heated surface throughout the material. Chen et al. [114] also recently developed a coupled approach between the fire and composite using CFD and finite element analysis (FEA) that considers the effects of changes in the boundary conditions and heat release due to decomposition of the polymer matrix.

The thermal model most often used to calculate the temperature distribution in composites exposed to fire was developed by Henderson et al. [97]. The thermal model analyses the energy transfer processes of heat conduction, pyrolysis of the polymer matrix, and diffusion of decomposition gases. The model is expressed as a one-dimensional non-linear equation that incorporates these processes:

$$\rho C_p \frac{\partial T}{\partial t} = k_{\perp} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{\perp}}{\partial x} \frac{\partial T}{\partial x} - \dot{m}_g C_{p(g)} \frac{\partial T}{\partial x} - \frac{\partial \rho}{\partial t} (Q_p + h_c - h_g) \quad (1)$$

where the enthalpies of the solid and gas phases are defined as:

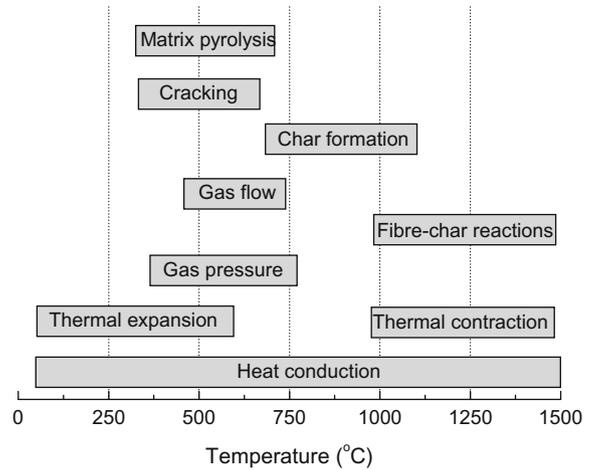


Fig. 2. Various responses of fibreglass laminate with temperatures. (The temperatures are approximate, and will depend on the polymer matrix and fire conditions).

$$h_c = \int_{T_{\infty}}^T C_p dT \quad (2)$$

$$h_g = \int_{T_{\infty}}^T C_{p(g)} dT \quad (3)$$

The first term on the right-hand side of Eq. (1) considers the effect of heat conduction in the through-thickness (transverse) direction. The second term also accounts for heat conduction, although it considers the influence of changing transverse thermal conductivity with increasing temperature. The first and second terms can be expanded to analyse two- and three-dimensional heat flow. The third term considers the internal convection of thermal energy due to the flow of hot decomposition gases towards the heated surface. The last term is the temperature change due to heat generation or consumption resulting from matrix decomposition.

Gibson et al. [113] modified slightly the thermal equation by Henderson et al. [97] to include the decomposition reaction rate of the polymer matrix:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_{\perp} \frac{\partial T}{\partial x} \right) - \dot{m}_g \frac{\partial}{\partial x} h_g - \rho A \left[ \frac{(m - m_f)}{m_o} \right]^n e^{-\frac{E}{RT}} (Q_p + h_c - h_g) \quad (4)$$

The last term is the decomposition term that defines the pyrolysis reaction rate of the polymer matrix, and the reaction rate constants ( $A$ ,  $E$ ,  $n$ ) must be measured using thermogravimetric analysis (TGA). This term is negative for endothermic and positive for exothermic decomposition reactions. By iteratively solving the equation for increasing temperature and time ( $\delta T/\delta t$ ) at the heated surface it is possible to calculate the temperature at any location

Table 1

Summary of the main processes when a composite is exposed to fire. The processes considered in the various thermal models is given. The symbols mean that the model considers (✓) or does not (×) consider the process. The numbers refer to the references describing the models.

	97	103	108	111	113
Heat conduction through virgin material and char	✓	✓	✓	✓	✓
Decomposition of polymer matrix and organic fibres	✓	✓	✓	✓	✓
Flow of gases from the reaction zone through the char zone	✓	✓	✓	✓	✓
Thermal expansion/contraction	×	✓	✓	✓	×
Pressure rise	×	✓	✓	✓	×
Formation of delamination, matrix cracks and voids	×	×	×	×	×
Reactions between char and fibre reinforcement	×	×	×	×	×
Ablation	×	×	✓	×	×

in the composite. It is also possible to calculate the mass loss and extent of charring, which are related to the decomposition term. The calculation of these processes is explained in the next section.

Validation of the model by experimental fire testing has shown that the thermal equations can predict the temperature at any location in polymer laminate and sandwich composite materials with good accuracy [59,70,71,74–76,78,97,102,113,115]. For example, Fig. 3 shows the agreement between the theoretical and measured temperature profiles at different locations through fibreglass laminate and sandwich composite material when exposed to a simulated fire condition.

The simplest thermal models analyse the effects of heat conduction, polymer decomposition and volatile gas flow on the temperature [97,112,113]. More sophisticated models also consider the effect of other processes which usually have a smaller influence on temperature than heat conduction, decomposition and gas flow. For example, Florio et al. [102] developed a thermal model that analyses the effects of heat conduction, gas flow, matrix decomposition as well as thermal expansion and internal pressure rise due to the formation of volatile gases. The full energy-balance equation is expressed as:

$$\rho C_p \frac{\partial T}{\partial t} = \dot{m}_g \Delta A_c \Delta x C_p \frac{\partial T}{\partial t} + \Delta A_c \Delta x \frac{\partial}{\partial x} \left( k_{\perp} \Phi \frac{\partial T}{\partial x} \right) + h_r \Delta A_c \Delta x (T_s - T_{\infty}) + \Delta A_c \Delta x \frac{D(\Phi p)}{Dt} - \frac{\partial m}{\partial t} [-h_g + h_g(T_s) + v^2/2] \quad (5)$$

The first term on the right-hand side of this equation accounts for the net rate of volatile gas flow, the second term considers the effect of heat conduction, the third term determines the net rate of energy transfer by convection of volatile gases, and fourth term accounts for the work rate of thermal expansion, and the last term accounts for thermal energy that is released or absorbed by the matrix decomposition reactions. Using the model, it is possible to predict the temperature, mass loss, porosity and volumetric expansion of the composite material as well as the temperature, pressure, mass flux and mass storage of the gases.

The thermal models presented by Eqs. (1), (3), and (5) assume a one-dimensional material system with heat transfer only occurring in the through-thickness direction. However, the models can be expanded to analyse two- and three-dimensional systems. The solution of the thermal models requires a large amount of empirical data on the thermal and decomposition properties of the composite. Thermal property data such as thermal conductivity and specific heat capacity must be experimentally determined over the temperature range of interest, which may be many hundreds of degrees. The decomposition reaction rate constants ( $A$ ,  $E$ ,  $n$ ) must also be measured over a large temperature range. Other properties must be assumed or estimated (e.g. decomposition gas velocity) because it is difficult to accurately measure the value.

Gibson et al. [116] recently proposed a simplified approach to modelling the temperature in composites exposed to fire which avoids the use of the Arrhenius decomposition model. Called the

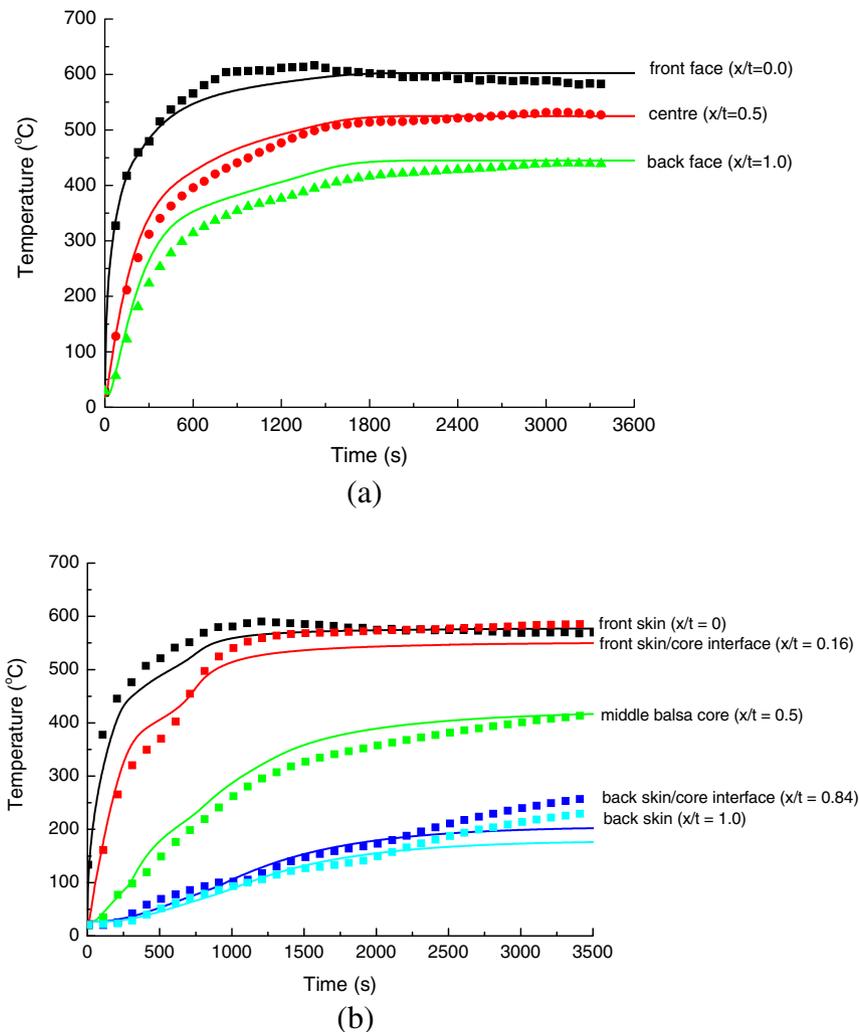


Fig. 3. Comparison of the theoretical (solid curves) and measured (data points) temperature profiles in a (a) woven glass–vinyl ester laminate [75] and (b) fibreglass–balsa core sandwich composite [78] when exposed to simulated fire conditions involving one-sided heating at the heat flux.

'apparent thermal diffusivity (ATD)' model, the rate dependence of the decomposition behaviour is neglected, with the decomposition state at any temperature being calculated directly from the TGA curve for the polymer matrix. The ATD model is simpler to solve than other thermal models, and is currently being validated against temperature data for several types of laminates exposed to fire.

## 2.2. Modelling thermal properties of decomposing composites

Accurate prediction of the thermal response of composites requires knowledge of the thermal and physical properties of the material over the temperature range of interest. The properties include density, thermal conductivity, specific heat capacity and gas permeability of both the virgin composite and fully decomposed (char) material. The properties change with temperature, and it is necessary to consider the temperature-dependence in the analysis.

The change in density with time due to decomposition and volatilisation of the polymer matrix can be determined in several ways. The most common approach uses Arrhenius decomposition kinetics. In the case of composites that decompose via a single-stage reaction process, the density change is calculated using:

$$\frac{\partial \rho}{\partial t} = -(\rho_v - \rho_c) \left[ \frac{\rho - \rho_c}{\rho_v - \rho_c} \right]^n A e^{(-E/RT)} \quad (6)$$

A large amount of theoretical and experimental work has been done on the thermal conductivity and specific heat capacity of composites prior to the onset of decomposition [117–127]. However, less information is available on the thermal properties of composites during the decomposition phase changes to the final char material [98,99,128,129]. Prior to decomposition, the thermal properties are those of the virgin composite material, while after decomposition the properties are those of the fully decomposed (char) material. The properties of the decomposing composite are assumed to be dependent on the relative mass fractions of the virgin composite and fully decomposed material. The mass fraction of virgin material in a decomposing composite is calculated using:

$$F = \frac{\rho - \rho_c}{\rho_v - \rho_c} \quad (7)$$

Using this as a progress variable for the extent of matrix decomposition, the thermal conductivity of a decomposing composite is defined as:

$$k(T) = F \cdot k_v(T) + (1 - F) \cdot k_c(T) \quad (8)$$

Lattimer and colleagues [129] have published thermal conductivity data for fibreglass laminates and glass fibre-char. Fig. 4 shows the effect of temperature on the thermal conductivity of a woven glass–vinyl ester laminate in the virgin and fully decomposed (char) states. The dependence of thermal conductivity on temperature is essential information for modelling the thermal response of composites in fire. However such information is lacking for most composite systems and must be measured experimentally. The change in thermal conductivity with temperature of the virgin composite and the char is often expressed using empirical curve-fit polynomial equations [100,129]:

$$k_v(T) = k_{1(v)} + k_{2(v)}T \quad (9)$$

and

$$k_c(T) = k_{1(c)} + k_{2(c)}T + k_{3(c)}T^2 + k_{4(c)}T^3 \quad (10)$$

Dimitrienko et al. [110] proposed an alternate method to calculate the change in thermal conductivity with temperature:

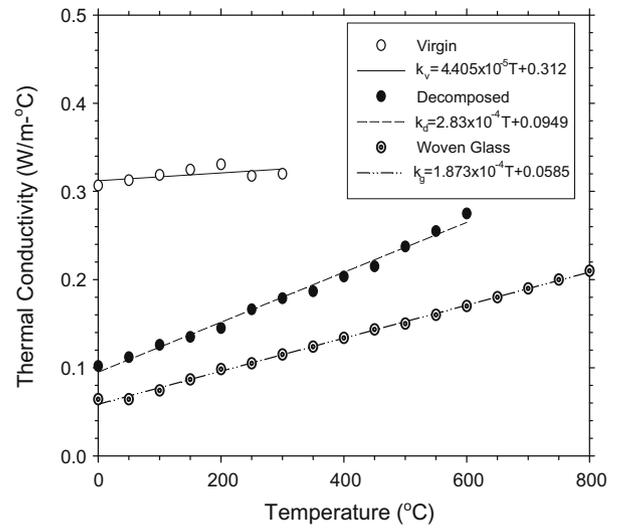


Fig. 4. Effect of temperature on the measured thermal conductivity of virgin glass–vinyl ester, fully decomposed glass–vinyl ester, and woven glass fibre. From Lattimer [129].

$$k = \frac{k_v}{(1 - V_m)} \left( \frac{T}{T_\infty} \right) (V_m + n_i V_c) \quad (11)$$

However, the validation of this equation using measured thermal conductivity property data for hot, decomposing composites has not been performed.

The specific heat capacity is determined using:

$$C_p(T) = F \cdot C_{p(v)}(T) + (1 - F) \cdot C_{p(c)}(T) \quad (12)$$

Henderson and Wiecek [100] report that the specific heat capacities for the virgin composite and char are functions of temperature, and are calculated by:

$$C_{p(v)}(T) = C_{p1(v)} + C_{p2(v)}T \quad (13)$$

and

$$C_{p(c)}(T) = C_{p1(c)} + C_{p2(c)}T \quad (14)$$

As with thermal conductivity, the specific heats for the virgin composite and decomposed (char) material must be measured experimentally over the temperature range of interest, and then these expressions are fitted to the data.

The thermal properties of composites may change with the evolution of fire-induced damage. For example, thermal conductivity of the virgin composite is reduced with the formation of delaminations which slows heat transport by creating an air gap between debonded ply layers. Most thermal models currently ignore the effect of delaminations, which results in an over-prediction of the temperatures in the virgin material shielded by the cracks. Luo and Desjardin [130] recently developed a model to calculate the change in the through-thickness thermal conductivity of laminates due to cracking:

$$k_\perp = (\varphi_s/k_v + \varphi_{cr}/k_{cr})^{-1} \quad (15)$$

where the volume fraction of cracks depends on the crack density and crack width.

## 2.3. Modelling thermal boundary conditions

The thermal boundary condition for the composite surface exposed to the fire is specified by the heat flux:

$$-k_{\perp} \left. \frac{\partial T}{\partial x} \right|_{x=0} = q''_{s,o} \quad (16)$$

The net surface heat flux into the composite is the combination of radiative and convective components, which is calculated by:

$$q''_{s,o} = (\varepsilon_s q''_{rad} - \varepsilon_s \sigma^* T_s^4) + h_{conv}(T_{\infty} - T_s) \quad (17)$$

The boundary condition on the unexposed side of the composite is also assumed to consist of convective and radiative components:

$$q''_{s,L} = \varepsilon \sigma (T_s^4 - T_{\infty}^4) + h_{conv}(T_s - T_{\infty}) \quad (18)$$

### 3. Damage modelling of composites in fire

#### 3.1. Fire-induced damage

Damage caused to laminates and sandwich composites in fire has been a topic of intensive investigation in recent years because of the influence on the structural properties [80–90,131–135]. Recent research has also revealed that the fire reaction behaviour, such as time-to-ignition, heat release rate and smoke density, are affected by the presence of fire-induced damage formed under tensile loading [136]. The fire-induced damage experienced by laminates includes matrix decomposition, pore formation, delamination cracking, matrix cracking, fibre–matrix debonding, and char formation. Fig. 5 shows the different types of damage that occur in

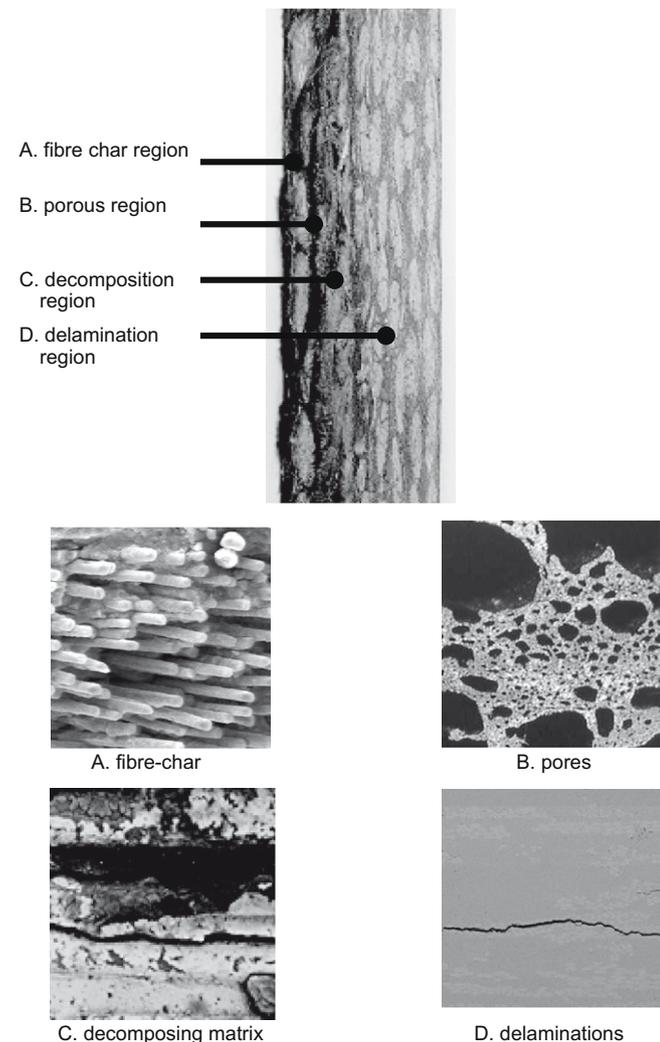


Fig. 5. Cross-sectional view of the fire-damaged laminate.

the through-thickness direction of a laminate. Moving inwards from the back (unheated) surface, the temperature in the virgin state is too low to cause decomposition of the polymer matrix, however maybe sufficiently high to introduce other damage. The damage includes delamination cracks between the plies, matrix cracks within the plies, and fibre–matrix interfacial cracks. Closer to the heated surface is a thin region called the decomposition (or pyrolysis) zone where the polymer matrix begins to decompose into char and gas. In this region the matrix is partially degraded, usually by scission of the chains into high molecular weight fragments, which causes high density crazing/cracking and pore formation. The next zone is the fibre-char state where the polymer matrix has completely decomposed to char and volatiles. The char will eventually volatilize by oxidation at high temperatures to produce the final state of fibre only when the fibres are thermally stable. Reactive fibres such as carbon will oxidize while organic fibres such as aramid and ultra-high molecular polyethylene will decompose.

Fire-induced damage to composite structures is difficult to accurately model because it is dependent on many parameters, with the main factors being the temperature and duration of the fire; the volumetric dilations and toughness properties of the material at high temperature; and the type and magnitude of external loading (including the boundary conditions). Some progress has been achieved in modelling the initiation and growth of voids, delaminations and char in polymer laminates [72,97,100,102,105,108–111,130,134]. However, the models currently consider only one type of damage, and a unified modelling approach that analyses concurrently the initiation and development of the many types of damage has not been developed.

#### 3.2. Modelling pore formation

Gas-filled pores develop in the polymer matrix and at the fibre–matrix interface during decomposition of composite materials in fire [106,107,137]. The pores initiate, grow and coalesce in the hot, viscous matrix under the high internal pressures exerted by decomposition gases. Sullivan and Salamon [103] developed a model based on the conservation of mass principle to calculate the diffusion of gases through a hot, decomposing composite. Dimitrienko et al. [111] formulated an analytical expression that relates the mass loss of the polymer matrix due to decomposition to the gas pressure in the pores:

$$\frac{\partial m}{\partial t} = A \left[ 1 - \frac{p}{p_o} e^{-(2E/RT)} \right]^{1/2} e^{-E/RT} \quad (19)$$

Florio et al. [120] calculated local pressure rises as high as 15 times above the ambient pressure for a phenolic matrix laminate. This is high enough to cause delamination damage, matrix cracking and fibre–matrix debonding. Florio and colleagues compared their predicted pressures to experimental measurements [138], and found that the peak pressures agree reasonably well at one location (9 vs. 9.7 atm). However, the experimental pressure decays much more rapidly with time than the predicted results. This behaviour was attributed to poor cement bonding between the hypodermic tubing and the specimen, magnified by difference in the thermal expansion of the cement and the specimen. Thus, Florio et al. [102] concluded that the actual pressures in the composite are at least as large as those measured experimentally. At another location, the agreement with the maximum pressure is much poorer (14.5 vs. 7.0 atm). However, Florio et al. indicate that it is “encouraging” that the maximum pressure measured experimentally occurs at the same time as that predicted. A recent numerical study by Zhang and Case [139] indicated that the internal pressures for

the decomposing composite material. Because of these difficulties, the role (if any) that pore formation plays in the failure of composites is still being investigated.

### 3.3. Modelling delamination damage

Delamination cracking occurs in laminates and sandwich materials exposed to fire, and this damage can severely weaken composite structures supporting compression or in-plane shear loads. The cracking is due to the internal pressure rise, thermally-induced strains caused by thermal expansion, and reduced interlaminar fracture toughness caused by matrix softening.

Models have been developed to predict the fire-induced strains due to thermal expansion [52–56,69,101,103,106,135,137]. The mechanical strain in laminates prior to the onset of matrix decomposition is calculated using:

$$\varepsilon(T) = \varepsilon_T - \alpha_v(T - T_\infty) \quad (20)$$

Analysing the thermal strains is more complicated once the matrix starts to decompose because the composite expands and contracts at different temperatures as it undergoes various phase changes. For instance, Fig. 6 shows the change in length of a glass-phenolic laminate and the responding phase changes with increasing temperature. Florio et al. [101] developed a model to predict the axial expansion of a decomposing composite exposed to fire. The strain is approximated using:

$$\frac{\partial \varepsilon(T)}{\partial t} = \alpha_v F \frac{\partial T}{\partial t} + \alpha_c (1 - F) \frac{\partial T}{\partial t} + \frac{\partial}{\partial t} \left( \eta T + \xi \frac{m}{m_o} \right) \quad (21)$$

McManus and Springer [108] also formulated a model for analysing the strain within a composite exposed to fire:

$$\varepsilon_{ij} = S\sigma + \Lambda_{ij}\Delta p + \alpha_{ij}\Delta T + \beta_{ij}\Delta(MC) + \chi_{ij}\Delta v \quad (22)$$

The terms on the right-hand side of this equation account respectively for the externally applied strain; internal strain arising from gas pressure; thermal expansion; vaporisation of moisture; and char formation. All the parameters must be determined experimentally before the total strain can be calculated. McManus and Springer [109] have shown that their model can predict the formation of delaminations in a laminate exposed to fire. Delamination cracking is assumed to occur when the magnitude of the strain calculated using Eq. (22) exceeds the intraply failure strain. Fig. 7 shows the effect of heating time on the maximum depth of delamination cracks in a carbon-phenolic laminate exposed to a propane

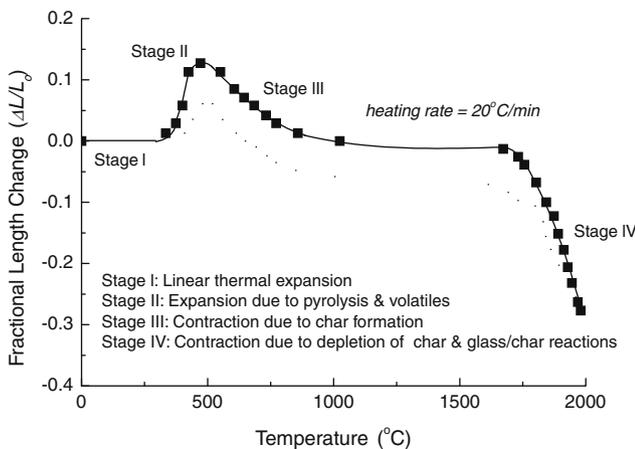


Fig. 6. Fractional length change with increasing temperature for a glass-phenolic laminate. The different stages of expansion and contraction are indicated. Data from Florio et al. [101].

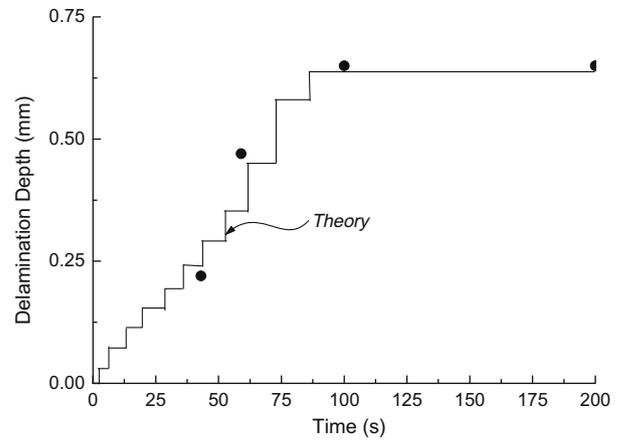


Fig. 7. Effect of heating time on the depth of delamination cracking in a carbon/phenolic laminate exposed to a gas flame.

flame. The data points and step-shaped curve show the measured and calculated depths of delamination cracking, respectively, and excellent agreement is observed.

Lua and colleagues [52–58] recently developed a finite element model that analyses the growth of delamination cracks in hot, decomposing laminates and sandwich composites using cohesive element techniques. This model considers the influence of reduced interlaminar toughness caused by matrix softening on the delamination cracking process.

The progress in modelling the thermal strains and resultant delamination cracking has not been matched by experimental research into the interlaminar fracture toughness properties of composites at high temperature. Analysis of delamination cracking requires experimental data on the interlaminar fracture toughness properties between the ambient and matrix decomposition temperatures (typically 300–400 °C). Published data on the elevated temperature interlaminar toughness properties of composites is mostly below 200 °C [e.g. 140–142], and higher temperature data up to decomposition is lacking.

### 3.4. Modelling decomposition and char formation

Modelling decomposition of the polymer matrix into volatile gases and char is important for analysing the phases changes and structural behaviour of composites in fire. The mass loss of a polymer that decomposes via a single-stage reaction process is calculated using the Arrhenius kinetic rate equation:

$$\frac{\partial m}{\partial t} = -Am_o \left( \frac{m - m_f}{m_o} \right)^n e^{(-E/RT)} \quad (23)$$

This equation (which is the same as Eq. (6) but expressed in mass) is solved using the reaction rate constants for the polymer (A, E, n). Eq. (23) gives a reasonable estimate of the mass loss, as shown in Fig. 8 for a woven glass-vinyl ester exposed to a simulated fire with a radiant heat flux of 50 kW/m<sup>2</sup>.

Modelling char formation is also important in analysing the decomposition and structural response of composites in fire. Mouritz and colleagues [72,86] have shown that Eq. (23) can be used to analyse the formation and growth of the char phase in laminates exposed to fire. It was observed that visible char formation in thermoset laminates starts when the mass fraction of the polymer matrix is reduced by ~20% due to decomposition and vaporisation. Using this as the criteria for char formation, the extent of char growth in laminates can be calculated based on the mass loss. Fig. 9 compares the theoretical and measured thickness of the char

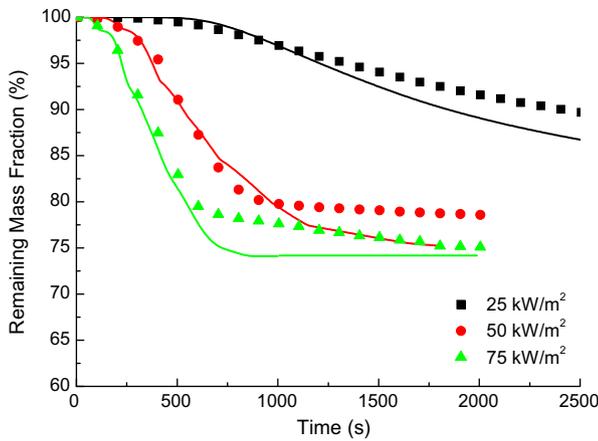


Fig. 8. Calculated (Eq. (24)) (solid curves) and measured (data points) mass loss of a woven glass–vinyl ester laminate exposed to simulated fire conditions at different heat flux values. Data adopted from [76].

zone in thermoset laminates when exposed to one-sided heating under simulated fire conditions. The char thickness ( $d_c$ ) is normalised to the total laminate thickness ( $d$ ). The initiation and growth of the char with increasing heating time can be predicted. Fig. 9 shows a compilation of char thickness values for a variety of laminates exposed to different heat flux conditions, and with the exception of a few outliers there is good agreement between the calculated (based on 20% mass loss) and the measured values. This progress in modelling the decomposition of the polymer matrix into char for laminates has not been matched by modelling for sandwich composites, where a validated char model that considers char formation in both the skins and organic core is lacking.

#### 4. Mechanical modelling of composites in fire

##### 4.1. Compression modelling of composites in fire

There has been major progress in recent years in the development of models to analyse the mechanical properties and failure of composites under combined compression loading and one-sided heating by fire [38–40,45,46,52–56,60–69,73–75]. The models analyse a composite panel that is loaded axially at a constant compression load while simultaneously being heated from one side by fire. The models use different mechanical theories to analyse the reduction to the compression properties as the material is heated by fire.

The mechanical analysis includes average strength [73–75], Euler buckling [68,69] and visco-elastic softening [60–63] for laminates and skin failure [78], buckling [42,44–46,68,69] and skin wrinkling [43] models for sandwich composites. The models also differ in the scale of the analysis, ranging from unit cell analysis of the individual fibres and polymer matrix [52–56] to ply-by-ply analysis [73] to bulk analysis in which the ply properties are smeared over the volume of material [68,69,74,75]. The models are solved analytically or using finite element methods.

While the models use different mechanical analysis to calculate the compression properties, they use the same analysis to calculate the thermal response of the material. The initial step in analysing the compression properties is the calculation of the temperature distribution through the composite with increasing time using thermal modelling. The temperature distribution is used to calculate the reduction to the mechanical properties through the composite. The models assume that the mechanical properties decrease in a single-stage (rigid-to-rubbery) glass transition of the polymer matrix with increasing temperature according to the trend depicted in Fig. 10. This shows the typical relationship between the matrix-dominated properties of a laminate and temperature for iso-thermal conditions. Matrix-dominated properties that show this temperature-dependence include compression modulus and strength. The reduction to the mechanical properties with increasing temperature cannot currently be calculated, but must be measured experimentally under iso-thermal conditions. The properties must be measured over the temperature range over

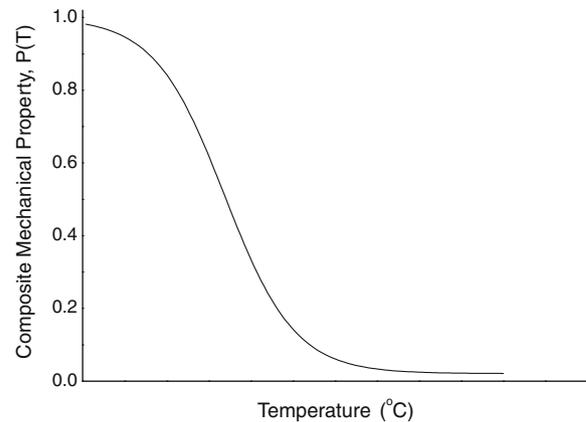


Fig. 10. Assumed reduction in the matrix-dominated properties of composites with increasing temperature.

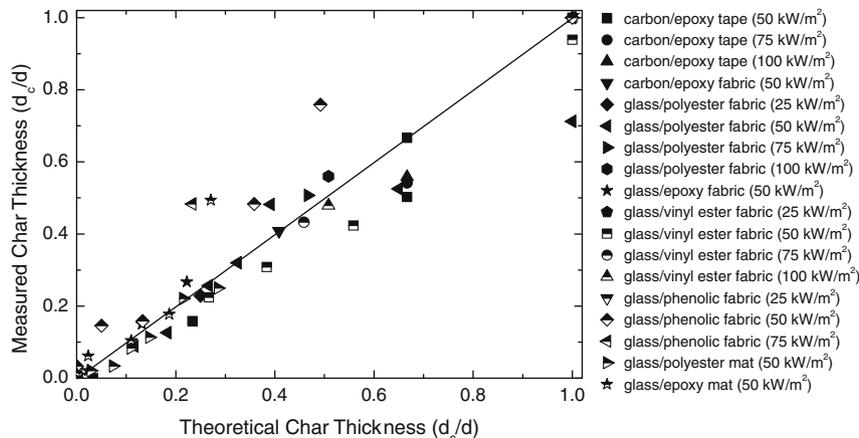


Fig. 9. Comparison of the calculated and measured thickness of the char zone in laminate materials exposed to simulated fire conditions of different heat flux values. The char thickness values ( $d_c$ ) are normalised to the laminate thickness ( $d$ ). Data from [86].

which softening occurs, which is usually 20–250 °C. The data is then fitted with an empirical expression relating the property to temperature.

Several curve-fitting analysis techniques can be used to fit the elevated temperature property data, including Prony series [60–63], polynomial [68,69,143], tanh functions [73–75] and others [144,145]. The polynomial equation used to relate property with temperature is expressed as:

$$P(T) = \left[ 1 - \xi_1^* \left( \frac{T - T_\infty}{T_g - T} \right) - \xi_2^* \left( \frac{T - T_\infty}{T_g - T} \right)^2 - \xi_3^* \left( \frac{T - T_\infty}{T_g - T} \right)^3 \right] \cdot P_o \tag{24}$$

and the tanh equation is:

$$P(T) = \left( \frac{P_o + P_R}{2} - \frac{P_o - P_R}{2} \tanh(\xi^*(T - T_g)) \right) \tag{25}$$

These equations are only valid when the composite softens in a single-stage process. Not all polymers undergo a single-stage loss in property, and certain types of thermosets (e.g. phenolics) and crystalline thermoplastics undergo multiple softening stages with increasing temperature, and the property relaxation cannot be described using the above expressions. Additional softening terms are needed. For example, when softening occurs over two temperature ranges then the tanh function (Eq. (25)) is extended:

$$P(T) = P_1 - \frac{P_1 - P_2}{2} \times \left( 1 + \tanh(\xi_1^*(T - T_{g(1)})) - \frac{P_2 - P_3}{2} (1 + \tanh(\xi_2^*(T - T_{g(2)}))) \right) \tag{26}$$

Eqs. (24)–(26) are used to calculate the property loss due solely to viscous softening of the polymer matrix, and do not consider the contributions of other softening processes. As yet, a mechanistic-based model that predicts the reduction to the mechanical properties due to viscous softening, pore formation, delamination, and other fire-induced damage caused by high temperatures has not been developed. Gibson et al. [73] developed an extended version of Eq. (25) that considers the effects of both viscous softening and decomposition of the polymer matrix:

$$P(T) = \left( \frac{P_o + P_R}{2} - \frac{P_o - P_R}{2} \tanh(\xi_*(T - T_g)) \right) R^n(T) \tag{27}$$

The first term on the right-side of the equation analyses viscous softening and the second term ( $R^n$ ) analyses softening caused by matrix decomposition.

Current approaches to modelling the compression response of composites to fire use empirical curve-fit equations (e.g. Eqs. (24)–(27)) to calculate the reduction to the compressive properties at many points through the composite based on the thermal profile. It is from this point in the analysis that the models use different mechanical theories to calculate the structural response and failure of the composite. It is not possible to give a complete description of all the mechanical models. Instead, the two modelling approaches which have been the most rigorously validated using experimental fire data – the average strength model [75] and visco-elastic softening model [63] – are described more fully. The reader is referred to the original papers for details of the other models [38,41–46,54,68,69,72,73].

The average strength model calculates the compression strength and survival time of laminates and sandwich composites in fire [75,78]. The model uses thermal analysis to calculate the temperature distribution and then iso-thermal mechanical analysis (Eq. (27)) to calculate the residual compression strength at different locations through the material. The local strength values are

averaged over the load-bearing area using Simpson integration to determine the reduction to the average bulk compression strength of the composite at any time during the fire event:

$$\sigma_{av} = \frac{1}{t_s} \int_0^{t_s} \sigma(x) dx \tag{28}$$

which expands to:

$$\int_0^{t_s} \sigma(x) dx = \frac{t_s}{3(\chi - 1)} [\sigma(x_0) + 4\sigma(x_1) + 2\sigma(x_2) + \dots + 2\sigma(x_{\chi-2}) + 4\sigma(x_{\chi-1}) + \sigma(x_\chi)] \tag{29}$$

The survival time of compression-loaded composites in fire can be calculated with good accuracy using the average strength model. When the average compression strength calculated using Eq. (29) falls below the applied compression stress then the composite is assumed to fail. This model does not take time-dependent softening into account, which is caused by viscoelastic and viscoplastic deformation of the polymer matrix or the presence of fire-induced damage such as delamination cracking. Despite ignoring these softening processes, the model gives a reasonable estimate of the compression strength and failure time of composites exposed for fire. Fig. 11 shows the effect of applied compression stress on the failure times of fibreglass laminate and fibreglass–balsa core sandwich materials when exposed to different heat flux levels. As

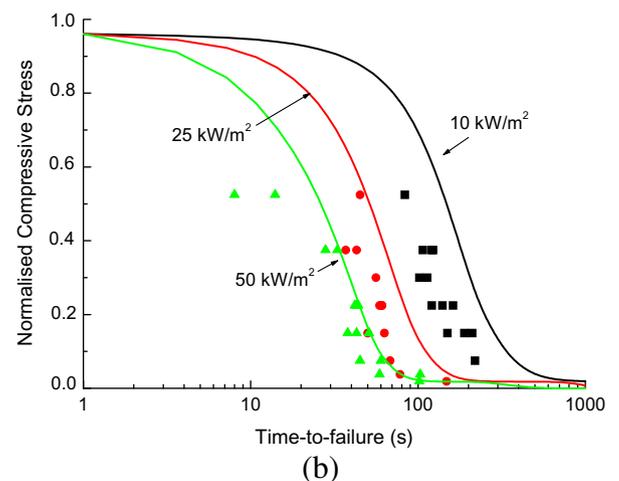
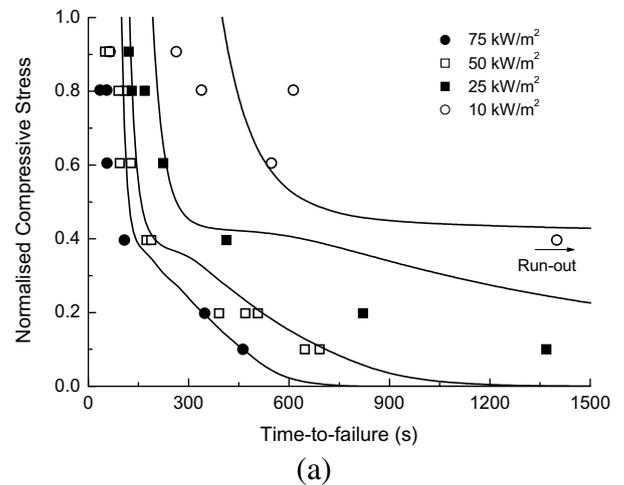


Fig. 11. Comparison of failure times calculated using the average strength model by Feih et al. [75] and measured experimentally for a (a) woven glass–vinyl ester laminate and (b) fibreglass–balsa core sandwich material. Results for (a) and (b) from Feih et al. [75] and [78], respectively.

expected, the failure times increase when the applied stress or heat flux is reduced. The curves show the theoretical failure times calculated using the average strength model and the data points show the experimental failure times. The average strength model can predict with reasonable accuracy the failure times of the laminate (that collapsed by plastic tow kinking), although the accuracy is not as good for the sandwich composite (that collapsed by front skin failure). This model has been validated for two types of composite (glass–vinyl ester, and carbon–epoxy) [75,78,79], and more rigorous validation with other materials, including thermoplastic laminates and sandwich materials, is required.

Case and colleagues [60–66] examined viscoelasticity influenced failures of laminates subjected to combined compression loading and one-sided heating by fire. In their initial analysis [63], a temperature-dependent shear modulus was used in the Budiansky and Fleck [146] kinking failure model. Subsequent work [64] used the time–temperature superposition principle to estimate the shear relaxation modulus, which is then used to develop a time–temperature dependent compression strength model:

$$\sigma_c(t, T, \tau) = G_{12}(t, T, \tau) \left[ 1 + n^* \left( \frac{3}{7} \right)^{\frac{1}{n^*}} \left( \frac{\bar{\phi}/\gamma_y}{n^* - 1} \right)^{\frac{n^* - 1}{n^*}} \right]^{-1} \quad (30)$$

Iso-thermal compression creep rupture tests were analysed using the shift factors obtained from shear creep compliance data, indicating that the same mechanism was active. In addition, Eq. (30) averaged through-the-thickness provided accurate predictions of the time-to-failure under these iso-thermal conditions. The analysis was also applied to the one-sided heating test, where the shear relaxation modulus is calculated as a function of temperature, time and applied stress. For laminates in which multiple fibre orientations are present, it is also necessary to account for stress redistribution within the laminate due to viscoelastic effects. Boyd et al. [62] used an implicit CLT analysis to calculate the stresses, and then applied Eq. (30) to calculate the strengths. This analysis highlights the two effects of viscoelasticity: the changes in stress distribution within the laminate and the changes in strength. To admit the analysis of structural geometries and more realistic fire scenarios, Zhang et al. [66] combined these viscoelastic effects with a Henderson-type decomposition analysis. Fig. 12 compares the calculated and measured failure times for a woven glass–vinyl ester laminate under combined compression loading and one-sided heating, where the calculated failure times were determined using the approach developed by Zhang et al. [66]. While the agreement is good, the kinking failure mode (as with the average strength model) has only been validated for a small number of composite systems, and further validation studies are required. A barrier to this additional validation as well as its more general application is the relatively large amount of material data required to determine the creep parameters for the composite.

Despite recent progress in the development of thermal–mechanical models for calculating the fire structural response and failure of composites under compression load, much remains to be done. The models assume that weakening is caused solely by matrix softening, and the effects of other softening processes such as pore formation and delamination are ignored. Further analysis which integrates these softening processes, as well as thermally-induced strains, into a compressive failure model for composites in fire is essential.

#### 4.2. Tension modelling of composites in fire

Modelling the fire structural response of composites under tension loading is more complicated than compression because softening and failure of both the polymer matrix and fibre reinforcement must be analysed. Less research has been performed

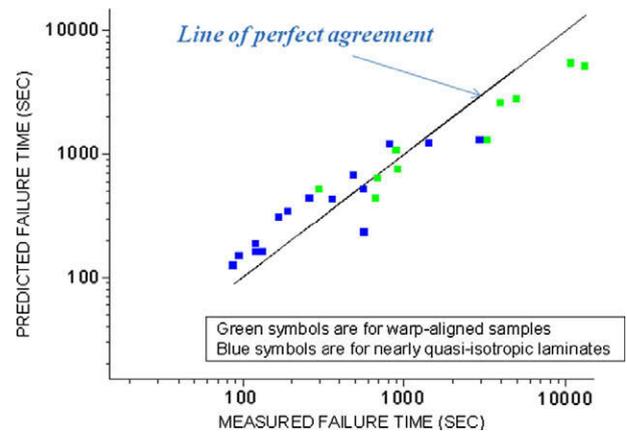


Fig. 12. Comparison of predicted and measured times to failure for one-sided compression tests applied to warp-aligned laminates of Vetrotex 324/Derakane 510A (blue symbols) and nearly-quasi-isotropic laminates (green symbols) [66]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

into the fire tension properties of composites than their compression properties [34,76]. Feih et al. [76] recently developed a modelling approach to analyse softening and failure of fibreglass laminates under combined tension and one-sided heating by fire. The model is based on the average strength approach described earlier for compression loading, with the notable difference that softening and tensile rupture of the fibres together with viscous softening and decomposition of the polymer matrix are analysed. The modelling approach involves calculating the temperature distribution through the laminate with increasing time using the thermal model. The reduction to the tensile strength of the polymer matrix due to softening and decomposition at different locations through the material is calculated based on the temperature profile. The loss in strength of the glass fibre reinforcement at different locations is calculated as a function of temperature and time:

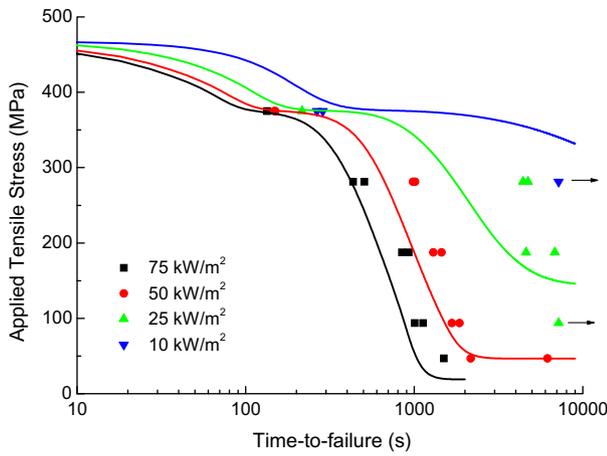
$$\sigma_{fb(j+1)}(T_{av(j+1)}(x_i), t_{eff,j+1}(x_i) + \Delta t) = \sigma_{fb(0)} - \sigma_{loss}(T_{av(j+1)}(x_i)) \tanh[\xi(T_{av(j+1)}(x_i))(t_{eff,j+1}(x_i) + \Delta t)] \quad (31)$$

This equation is only valid for silica-based fibres. Different fibre strength analysis which considers thermo-oxidation is required for carbon fibres, although this has not yet been performed.

The tensile strength of the laminate at different locations is calculated using rule-of-mixtures analysis that combines the elevated temperature properties of the matrix and fibres. The average tensile strength of the laminate is then computed using the Simpson integration method (Eqs. (28) and (29)). This modelling approach can estimate the tensile strength and failure rupture time of fibreglass laminates in fire. For example, Fig. 13 compares the theoretical and experimental failure times for a woven glass–vinyl ester laminate under tension when exposed to different heat flux levels. The model can estimate the failure times with reasonable accuracy. Like the compression failure models, the tension model by Feih et al. [76] does not analyse all the damage processes which control the mechanical properties and failure. The effects of thermal strain, pore formation, delamination and fibre–matrix debonding are not considered, and the development of new models that consider these processes in determining the tensile structure response is required. A model to analyse the tensile response of sandwich composites exposed to fire is also required.

#### 4.3. Post-fire mechanical models for composites

Progress in the analysis of the mechanical properties of composite materials following fire exposure is examined in this section.



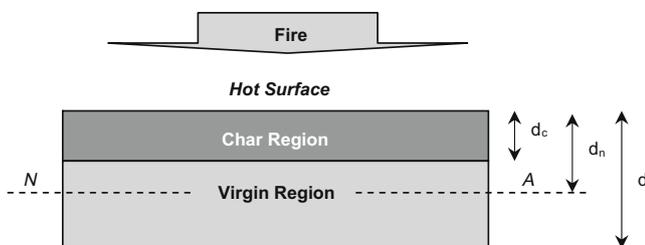
**Fig. 13.** Comparison of failure times calculated using the average strength model by Feih et al. [76] and measured experimentally for woven glass–vinyl ester laminate under combined tension loading and one-sided heating at different heat fluxes.

After a fire is extinguished, it is important to analyse the post-fire properties at room temperature to assess the residual mechanical integrity and safety of the structure. A large body of published experimental data reveals that the post-fire properties of laminates are determined mainly by the fire temperature, heating time, load condition (e.g. tension, or compression), and the decomposition properties of the polymer matrix [7,13,72,80–89,133,147,148]. Less information is available on the post-fire properties of sandwich composite materials [90].

The two-layer model is the most established analytical method for calculating the post-fire properties of laminates [80]. The model basically analyses a fire-damaged laminate as a two-layer structure consisting of fully decomposed (fibre-char) material and virgin material, as represented in Fig. 14. It is assumed the virgin zone has the same mechanical properties as the original (pre-fire) composite material because it is considered that thermal softening (prior to decomposition) of the matrix is fully recovered when cooled to room temperature. The model does not consider the presence of fire-induced damage inside the virgin zone, such as delaminations.

A fire-damaged laminate is modelled as a two-layer structure consisting of fibre-char and virgin material with the two phases having different mechanical properties at room temperature. Mouritz and Mathys [80,81] developed analytical expressions that combine the properties of the fibre-char and virgin phases to calculate the post-fire mechanical properties. The following expressions are used to calculate the post-fire tension, compression and bending (four-point) modulus, respectively:

$$E_t = \left( \frac{d - d_c}{d} \right) E_{t(o)} + \left( \frac{d_c}{d} \right) E_{t(char)} \quad (32)$$



**Fig. 14.** Idealised two-layer structure of fire-induced damage in a laminate. N–A refers to the neutral axis shown by the dashed line.

$$E_c = \left( \frac{d - d_c}{d} \right) E_{c(o)} + \left( \frac{d_c}{d} \right) E_{c(char)} \quad (33)$$

$$E_f = \frac{4E_{f(o)}}{d^3} \left[ (d - d_n)^3 + (d_n - d_c)^3 + \frac{E_{f(char)}}{E_{f(o)}} \left[ d_n^3 - (d_n - d_c)^3 \right] \right] \quad (34)$$

The post-fire failure loads under tension, compression (Euler buckling), and bending (four-point) are calculated using:

$$P_t = \left( \frac{d - d_c}{d} \right) P_{t(o)} + \left( \frac{d_c}{d} \right) P_{t(char)} \quad (35)$$

$$P_c = \frac{C\pi^2 E_c b (d - d_c)^3}{12L_c^2} \quad (36)$$

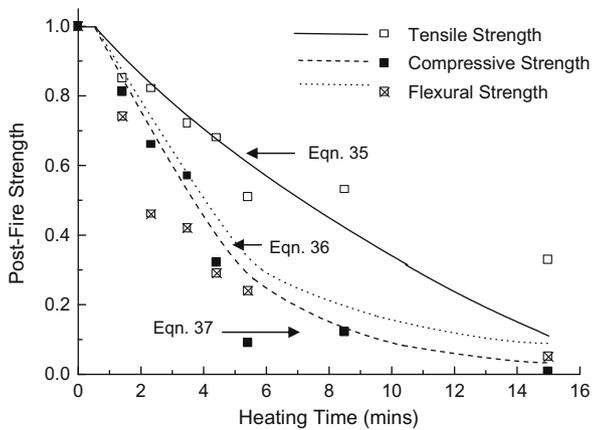
$$P_f = \frac{8\sigma_{f(o)} b}{3L_f} \left[ (d - d_n)^2 + \frac{(d_n - d_c)^3}{(d - d_n)} + \frac{E_{f(c)}}{E_{f(o)}} \cdot \frac{[d_n^3 - (d_n - d_c)^3]}{(d - d_n)} \right] \quad (37)$$

The key variable in calculating the post-fire properties is the thickness of the fibre-char zone ( $d_c$ ). The fibre-char thickness is determined by firstly calculating the temperature distribution through the laminate using the thermal model, and then using the temperature values to calculate the extent of char formation with the decomposition model. Char formation is assumed to occur when the mass loss of the polymer matrix reaches 20% due to decomposition and volatilisation (as described in Section 3.4).

Mouritz and colleagues [80–90] validated the two-layer model with post-fire mechanical property data measured for a variety of thermoset laminates tested under a range of heat flux and heating time conditions. The agreement between the calculated and measured post-fire properties is usually good. Fig. 15 shows the reduction to the post-fire tension, compression and flexural strengths of a woven glass–vinyl ester laminate following exposure to the heat flux of 50 kW/m<sup>2</sup> for increasing time. The curves show the theoretical reduction to the post-fire strength properties calculated using the two-layer model, and there is reasonable agreement with the experimental strength values. Mouritz and Gardiner [90] have developed a two-layer model to calculate the post-fire compression properties of sandwich composites, which has also been validated with experimental data. However, models to calculate the post-fire tension and bending properties of sandwich materials have not been developed.

## 5. Conclusions & future research

Major advances in the structural modelling of polymer composites have been achieved in recent years, however further analysis and validation against experimental data is required. Thermal models have been developed to calculate the temperature distribution in laminates and sandwich composites exposed to fire. These models can predict with good accuracy the temperature rise in composites containing non-reactive fibres (e.g. fibreglass). However, the capability of thermal models to analyse the temperature of composites containing reactive fibres (e.g. carbon, Kevlar), where oxidation and decomposition of the fibres influence the temperature, has not been adequately addressed. Furthermore, thermal models do not consider the influence of fire-induced damage, such as delamination cracking and skin-core debonding, on the heat flow process. New thermal models are currently being developed which consider fire-induced damage, however their accuracy has not been established against experimental temperature data.



**Fig. 15.** Comparison of the theoretical and measured reductions to the post-fire tension, compression and bending strengths of glass/polyester beam after exposure to the heat flux of  $50 \text{ kW/m}^2$  for increasing time. The post-fire strengths are normalised to the original strength of the composite.

The modelling of fire-induced damage is critical to the fire structural analysis of composites. There has been good progress in the development and validation of models to predict matrix decomposition and char formation. There has also been some progress in modelling the formation and growth of delaminations and gas-filled pores. However, most of the models restrict the analysis to a single type of damage, and the challenge is the development of a unified damage model that analyses concurrently all types of damage including fibre–matrix debonding, intraply matrix cracking and fibre damage.

Several mechanical models have been recently developed to analyse the fire structural response and failure of laminates and sandwich composites under compression loading. A model has also been developed for the tensile structural response of laminates to fire. However, models for analysing the tensile response of sandwich composites are not available. Furthermore, models to analyse the fire structural behaviour of composites under loading conditions other than tension and compression, such as shear, torsion and fatigue have not been developed. There is a need to improve the numerical robustness of existing models in solving highly non-linear behaviour. Lastly, there is a need to develop mechanistic-based models which accurately analyse the mechanisms and processes controlling the temperature distribution, damage, softening and failure. The development of mechanistic models will not only improve the accuracy of the predictions, but will reduce the reliance on large amounts of empirical data. The growing use of composites in high fire risk applications demands the on-going development of fire structural models for laminates and sandwich materials.

## Acknowledgements

The authors acknowledge funding support from the US Office of Naval Research (Grant Nos. N00014-04-10026, N00014-07-10514, N00014-03-1-0369 and N00014-06-1-0623) managed by Dr Luise Couchman. The research work by APM, SF, EK, and ZM was performed as a part of the Cooperative Research Centre for Advanced Composite Structures (Project 2.1.2).

## References

- [1] Mouritz AP, Gibson AG. Fire properties of polymer composite materials. Dordrecht: Springer; 2006.
- [2] Ventriglio DR. Fire safe materials for navy ships. *Naval Eng J* 1982;34:65–74.
- [3] Fisher KJ. Is fire a barrier to shipboard composites? *Adv Compos* 1993;23:20–6.

- [4] Lyon RE. Federal aviation administration research in fire safe materials for aircraft interiors. In: Proceedings of the international SAMPE symposium, vol. 41. CA: Anaheim; 1996. p. 344–50.
- [5] Sorathia U, Lyon R, Gann R, Gritzko L. Materials and fire threat. *SAMPE J* 1996;32:8–15.
- [6] Brown JE, Braun E, Twilley WH. Cone calorimetry evaluation of the flammability of composite materials. NBS Report NBSIR 88-3733; 1988.
- [7] Sorathia U, Dapp T, Kerr J. Flammability characteristics of composites for shipboard and submarine internal applications. In: Proceedings of the 36th international SAMPE symposium. San Diego, CA; 15–18 April 1991. p. 1868–78.
- [8] Hume J. Assessing the fire performance characteristics of GRP composites. In: International conference on materials and design against fire, London; 1992. p. 11–5.
- [9] Tewarson A, Macaione DP. Polymers and composites – an examination of fire spread and generation of heat and fire products. *J Fire Sci* 1993;11:421–41.
- [10] Scudamore MJ. Fire performance studies on glass-reinforced plastic laminates. *Fire Mater* 1994;18:313–25.
- [11] Brown JR, Fawell PD, Mathys Z. Fire-hazard assessment of extended-chain polyethylene and aramid composites by cone calorimetry. *Fire Mater* 1994;18:167–72.
- [12] Egglestone GT, Turley DM. Flammability of GRP for use in ship superstructures. *Fire Mater* 1994;18:255–60.
- [13] Sorathia U, Telegadas H, Bergen M. Mechanical and flammability characteristics of phenolic composites for naval applications. In: Proceedings of the 39th international SAMPE symposium; 11–14 April 1994. p. 2991–3002.
- [14] Gibson AG, Hume J. Fire performance of composite panels for large marine structures. *Plast Rub Compos* 1995;23:175–83.
- [15] Brown JR, StJohn NA. Fire-retardant low-temperature-cured phenolic resins and composites. *TRIP* 1996;4:416–20.
- [16] Sastri SB, Armistead JP, Keller TM. Phthalonitrile–carbon fiber composites. *Polym Compos* 1996;17:816–22.
- [17] Brown JR, Mathys Z. Reinforcement and matrix effects on the combustion properties of glass reinforced polymer composites. *Composites* 1997;28A:675–81.
- [18] Hsieh FY, Beeson HD. Flammability testing of flame-retarded epoxy composites and phenolic composites. *Fire Mater* 1997;21:41–9.
- [19] Grenier AT, Dembsy NA, Barnett JB. Fire characteristics of cored composite materials for marine use. *J Fire Safety* 1998;30:137–59.
- [20] Le Bras M, Bourbigot S, Mortaigne B, Cordellier G. Comparative study of the fire behaviour of glass–fibre reinforced unsaturated polyesters using a cone calorimeter. *Polym Polym Compos* 1998;6:535–9.
- [21] Dembsy NA, Jacoby DJ. Evaluation of common ignition models for use with marine cored composites. *Fire Mater* 2000;24:91–100.
- [22] Koo JH, Muskopf B, Venumbaka S, Van Dine R, Spencer B, Sorathia U. Flammability properties of polymer composites for marine applications. In: Proceedings of the 32nd international SAMPE technical conference; 5–9 November 2000 [Paper No. 136].
- [23] Lyon RE, Demario J, Walters RN, Crowley S. Flammability of glass fiber-reinforced polymer composites. In: Proceedings of the fourth conference on composites in fire, 15–16 September 2005, Newcastle-upon-Tyne, UK; 2005.
- [24] Mouritz AP. Fire safety of advanced composites for aircraft. Australian Transport Safety Bureau Report B2004/0046; 2006.
- [25] Mouritz AP. Review of smoke toxicity of fiber–polymer composites used in aircraft. *J Aircraft*; 2009;46:737–45.
- [26] Lattimer BY, Campbell T. Fire modeling of composites. In: Mouritz AP, Gibson AG, editors. Fire properties of polymer composite materials. Dordrecht: Springer; 2006. p. 103–32.
- [27] Ritchie SJ, Steckler KD, Hamins TG, Cleary TG, Yang JC, Kashiwagi T. The effect of sample size on the heat release rate of charring materials. In: Proceedings of the 5th international symposium on fire safety science; 1997. p. 177–8.
- [28] McGrattan K, Hostikka S, Floyd J, Baum H, Rehm R, Mell W, et al. Fire dynamics simulator (version 5) technical reference guide, NIST Report 1018-5; 2009.
- [29] Prasad K, Baum HR. Coupled fire dynamics and thermal response of complex building structures. *Proc Combust Inst* 2005;30:2255–62.
- [30] Lattimer BY, Ouellette J, Sorathia U, Satterfield D. Fire performance of composite helicopter hangar test articles, NSWCCD-TR-64-2003/01, vols. 1–5, West Bethesda, MD; 2003.
- [31] Lattimer BY, Ouellette J, Sorathia U. Large-scale fire resistance tests on sandwich composite materials. In: Proceedings of SAMPE 04, Long Beach, CA; 2004.
- [32] Greene E. Marine composites. <[www.marinecomposites.com](http://www.marinecomposites.com)>.
- [33] Potocki ML, Tuttle ME, Mescher AM. Behavior of polymeric composites exposed to a heat flux simulating fire. In: Proceedings of the conference on mechanical behavior of advanced materials, vol 84, 1998, ASM. p. 325–32.
- [34] Griffis CA, Nemes JA, Stonesifer FR, Chang CI. Degradation in strength of laminated composites subjected to intense heating and mechanical loading. *J Compos Mater* 1986;20:216–35.
- [35] Chang CI. Thermal effects on polymer composite structures. *Theor Appl Fract Mech* 1986;6:113–20.
- [36] Perring GA, Farrell PV, Springer GS. Degradation of tensile and shear properties of composites exposed to fire or high temperature. *J Compos Mater* 1989;14:54–66.
- [37] McManus HL, Springer GS. High temperature behavior of thermomechanical behavior of carbon–phenolic and carbon–carbon composites, I. Analysis. *J Compos Mater* 1992;26:230–55.

- [38] Dao M, Asaro RJ. A study on failure prediction and design criteria for fiber composites under fire degradation. *Composites* 1999;30A:123–31.
- [39] Krysl P, Ramroth W, Asaro RJ. FE modeling of FRP sandwich panels exposed to heat: uncertainty analysis. In: Proceedings of the SAMPE technical conference & exhibition, 16–20 May 2004, Long Beach, CA; 2004.
- [40] Krysl P, Ramroth WT, Steward LK, Asaro RJ. Finite element modeling of fibre reinforced polymer sandwich composites exposed to heat. *Int J Numer Methods Eng* 2004;61:49–68.
- [41] Asaro RJ, Krysl P, Ramroth WT. Structural fire integrity of FRP composites: analysis and design. In: Couchman L, Mouritz AP, editor. Modeling of naval composite structures in fire, Melbourne: Acclaim Printing; 2006.
- [42] Gu P, Asaro RJ. Distortion of polymer matrix composite panels under transverse thermal gradients. *Compos Struct* 2008;82:413–21.
- [43] Gu P, Asaro RJ. Wrinkling of sandwich polymer matrix composite panels under transverse thermal gradients. *Fire Saf J* 2008;43:151–60.
- [44] Gu P, Asaro RJ. Designing polymer matrix composite panels for structural integrity in fire. *Compos Struct* 2008;84:300–9.
- [45] Gu P, Asaro RJ. Designing sandwich polymer matrix composite panels for structural integrity in fire. *Compos Struct* 2009;88:461–7.
- [46] Asaro RJ, Lattimer B, Ramroth W. Structural response of FRP composites during fire. *Compos Struct* 2009;87:382–93.
- [47] Luo C, Xie W, Desjardin PE. Numerical simulation of composite structure response from a fire plume. In: Proceedings of the SAMPE 2005 symposium & exhibition.
- [48] Luo C, Xie W, Desjardin PE. Fluid–structure simulations of composite material response for fire environments. In: Couchman L, Mouritz AP, editors. Modeling of naval composite structures in fire. Melbourne: Acclaim Printing; 2006.
- [49] Luo C, Desjardin PE. Thermo-mechanical damage modeling of a glass-phenolic composite material. *Compos Sci Technol* 2007;67:1475–88.
- [50] Xie W, Desjardin PE. An embedded upward flame spread modeling based on 2D direct numerical simulation. *Combust Flame* 2009;156:522–30.
- [51] Xie W, Desjardin PE. A level set embedded interface method for conjugate heat transfer simulation of low speed 2D flows. *Comput Fluids* 2008;37:1262–75.
- [52] Lua J, O'Brien J. Fire simulation for woven fabric composites with temperature and mass dependent thermal-mechanical properties. In: Proceeding of composites in fire 3, Newcastle-upon-Tyne, UK; 9–10 September 2003.
- [53] Lua J, Key CT, O'Brien J, Lopez-Anido RA, El-Chiti FW, Dagher H, et al. Validation of a woven fabric analyzer using composite material strain measurements from a digital image correlation system. In: Proceedings of the Joint American Society For Composites/American Society For Testing and Materials Committee D30, 17–20 October 2004, Atlanta, GA; 2004.
- [54] Key CT, Lau J. Constituent based analysis of composite materials subjected to fire conditions. *Composites* 2006;37A:1005–14.
- [55] Lua J, O'Brien J, Key CT, Wu Y, Lattimer BY. A temperature and mass dependent thermal model for fire response prediction of marine composites. *Composites* 2006;37A:1024–39.
- [56] Lua J. Thermal-mechanical cell model for unbalanced plain weave woven fabric composites. *Composites* 2007;38A:1019–37.
- [57] Lua J, Shi P, Desjardin P, Case S. Fire simulation and thermal-mechanical damage prediction tool for composite structures. In: Proceedings of the 49th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference, 7–10 April 2008, Schaumburg, IL; 2008.
- [58] Luo CL, Chen L, Lua J, Shi J. A 3D Abaqus toolkit for thermal-mechanical damage prediction tool for composite structures. In: Proceedings of the 50th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference, 4–7 May 2008, Palm Springs, CA; 2008.
- [59] Looyeh MRE, Rados K, Bettess P. Thermomechanical response of sandwich panels to fire. *Finite Elem Anal Des* 2001;37:913–27.
- [60] Bausano JV, Boyd SE, Lesko JJ, Case SW. Composite life under sustained compression and one sided simulated fire exposure: characterization and prediction. In: Composites 2004 convention and trade show American Composites Manufacturers Association. Tampa, Florida; 2004.
- [61] Boyd SE, Lesko JJ, Case SW, Bausano JV. The viscoelastic/viscoplastic characterisation of glass-vinyl ester composites under fire conditions. In: Gibson AG, editor. Proceedings of composites in fire – 4, 15–16 September 2005, University of Newcastle upon Tyne, CompositeLink; 2005.
- [62] Boyd SE, Bausano JV, Lesko JJ, Case SW. Mechanistic approach to structural modelling of composites. In: Couchman L, Mouritz AP, 2006, editors. Modeling of naval composite structures in fire. Melbourne: Acclaim Printing; 2006.
- [63] Bausano JV, Lesko JJ, Case SW. Composite lifetime during combined compressive loading and one-sided simulated fire exposure: characterization and prediction. *Composites* 2006;37A:1092–100.
- [64] Boyd SE, Lesko JJ, Case SW. Compression creep rupture behavior of a glass/vinyl ester composite laminate subject to fire loading conditions. *Compos Sci Technol* 2007;67:3187–95.
- [65] Boyd SE, Case SW, Lesko JJ. Compression creep rupture behavior of a glass/vinyl ester composite subject to isothermal and one-sided heat flux conditions. *Composites* 2007;38:1462–72.
- [66] Zhang Z, Case SW, Lua J. A model and finite element implementation for the thermo-mechanical analysis of polymer composites exposed to fire. In: Proceedings of the 17th international conference on composite materials, 27–31 July 2009, Edinburgh, UK; 2009.
- [67] Summers PT, Lattimer BY, Feih S. Time-to-failure predictions for polymer laminates in fire. In: Proceedings of the 17th international conference on composite materials, 27–31 July 2009, Edinburgh, UK; 2009.
- [68] Lui L, Holmes JW, Kardomateas GA, Birman V. Compressive response of composites under combined fire and compressive loading. In: Gibson AG, editor. Proceedings of composites in fire – 4, 15–16 September 2005, University of Newcastle upon Tyne, CompositeLink; 2005.
- [69] Liu L, Kardomateas GA, Birman V, Holmes JW, Simitses GJ. Thermal buckling of a heat exposed, axially restrained composite column. *Composites* 2006;37A:972–80.
- [70] Dodds N, Gibson AG, Dewhurst D, Davies JM. Fire behaviour of composite laminates. *Composites* 2000;31A:689–702.
- [71] Looyeh MRE, Bettess P, Gibson AG. A one-dimensional finite element simulation for the fire-performance of GRP panels for offshore structures. *Int J Numer Methods Heat Fluid Flow* 1997;7:609–25.
- [72] Gibson AG, Wright PNH, Wu Y-S, Mouritz AP, Mathys Z, Gardiner CP. The integrity of polymer composites during and after fire. *J Compos Mater* 2004;38:1283–308.
- [73] Gibson AG, Wu Y-S, Evans JT, Mouritz AP. Laminate theory analysis of composites under load in fire. *J Compos Mater* 2006;40:639–58.
- [74] Feih S, Mathys Z, Gibson AG, Mouritz AP. Modelling the tension and compression strengths of polymer laminates in fire. *Compos Sci Technol* 2007;67:551–64.
- [75] Feih S, Mathys Z, Gibson AG, Mouritz AP. Modelling the compression strength of polymer laminates in fire. *Composites* 2007;38A:2354–65.
- [76] Feih S, Mouritz AP, Mathys Z, Gibson AG. Tensile strength modelling of glass fiber-polymer composites in fire. *J Compos Mater* 2007;41:2387–410.
- [77] Easby RC, Feih S, Konstantis C, La-Delfa G, Urso Miano V, Elmughrabi A, et al. A failure model for phenolic and polyester pultrusions under load in fire. *Plast Rub Compos* 2007;36:379–88.
- [78] Feih S, Mathys Z, Gibson AG, Mouritz AP. Modelling compressive skin failure of sandwich composites in fire. *J Sand Struct Mater* 2008;10:217–45.
- [79] Burns LA, Feih S, Mouritz AP. Composite properties of carbon-epoxy laminate in fire. *J Aircraft*; submitted for publication.
- [80] Mouritz AP, Mathys Z. Post-fire mechanical properties of marine polymer composites. *Compos Struct* 1999;47:643–53.
- [81] Mouritz AP, Mathys Z. Post-fire mechanical properties of glass-reinforced polyester composites. *Compos Sci Technol* 2001;61:475–90.
- [82] Mathys Z, Gardiner CP, Mouritz AP. Tensile and compressive properties of GRP composites with localised heat damage. *Appl Compos Mater* 2002;9:353–67.
- [83] Mouritz AP. Post-fire flexural properties of polyester-, epoxy- and phenolic-based composites. *J Mater Sci* 2002;37:1377–86.
- [84] Mathys Z, Mouritz AP, Gardiner CP, Townsend CR. Mechanical properties of GRP composites with localised heat damage. *Int J Mater Prod Technol* 2002;17:134–42.
- [85] Mouritz AP. Simple models for determining the mechanical properties of burnt FRP composites. *Mater Sci Eng A* 2003;359:237–46.
- [86] Gibson AG, Wright PHN, Wu YS, Mouritz AP, Mathys Z, Gardiner CP. Modelling residual mechanical properties of composites after fire. *Plast Rub Compos* 2003;32:81–90.
- [87] Mouritz AP. Fire resistance of aircraft composite laminates. *J Mater Sci Lett* 2003;22:1507–9.
- [88] Gardiner CP, Mathys Z, Mouritz AP. Post-fire structural properties of burnt GRP plates. *Marine Struct* 2004;17:53–73.
- [89] Mouritz AP, Mathys Z, Gardiner CP. Thermomechanical modelling the fire properties of fibre-polymer composites. *Composites* 2004;35B:467–74.
- [90] Mouritz AP, Gardiner CP. Post-fire properties of sandwich polymer composites. *Composites* 2002;33A:609–20.
- [91] Bamford CH, Malan DH. The combustion of wood, part 1. *Proc Camb Philos Soc* 1946;42:166–82.
- [92] Munson TR, Spindler RJ. Transient thermal behaviour of decomposing materials: part 1 general theory and application to convective heating. RAD-TR-61-10, AVCO Corporation; May 1961.
- [93] Kung HC. A mathematical model of wood pyrolysis. *Combust Flame* 1972;18:185–95.
- [94] Murty KA. Thermal decomposition kinetics of wood pyrolysis. *Combust Flame* 1977;29:311–24.
- [95] Kansa EJ, Perlee HE, Chaiken RF. Mathematical model of wood pyrolysis including internal forced convection. *Combust Flame* 1977;29:311–24.
- [96] Fredlund B. Modelling of heat and mass transfer in wood structures during fire. *Fire Safety J* 1993;20:39–69.
- [97] Henderson JB, Wiebelt JA, Tant MR. A model for the thermal response of polymer composite materials with experimental verification. *J Compos Mater* 1985;19:579–95.
- [98] Tant MR, Henderson JB, Boyer CT. Measurement and modelling of the thermochemical expansion of polymer composites. *Composites* 1985;16:121–6.
- [99] Henderson JB, Doherty MP. Measurement of selected properties of a glass-filled polymer composite. *High Temp-High Press* 1987;19:95–102.
- [100] Henderson JB, Wiecek TE. A mathematical model to predict the thermal response of decomposing, expanding polymer composites. *J Compos Mater* 1987;21:373–93.
- [101] Florio J, Henderson JB, Test FL. Measurement of the thermochemical expansion of porous composite materials. *High Temp-High Press* 1989;21:157–65.

- [102] Florio J, Henderson JB, Test FL, Hariharan R. A study of the effects of the assumption of local-thermal equilibrium on the overall thermally-induced response of a decomposition, glass-filled polymer composite. *Int J Heat Mass Transfer* 1991;34:135–47.
- [103] Sullivan RM, Salamon NJ. A finite element method for the thermochemical decomposition of polymeric materials—I. Theory. *Int J Eng Sci* 1992;30:431–41.
- [104] Sullivan RM, Salamon NJ. A finite element method for the thermochemical decomposition of polymeric materials—II. Carbon phenolic composites. *Int J Eng Sci* 1992;30:939–51.
- [105] Sullivan RM. A finite element method for thermochemically decomposing polymers. PhD dissertation, The Pennsylvania State University; 1990.
- [106] Sullivan RM. A coupled solution method for predicting the thermostructural response of decomposing, expanding polymeric composites. *J Compos Mater* 1993;27:408–34.
- [107] Pering GA, Farrell PV, Springer GS. Degradation of tensile and shear properties of composites exposed to fire or high temperature. *J Compos Mater* 1980;14:54–66.
- [108] McManus HL, Springer GS. High temperature behaviour of thermomechanical behaviour of carbon–phenolic and carbon–carbon composites, I. Analysis. *J Compos Mater* 1992;26:206–29.
- [109] McManus HL, Springer GS. High temperature behaviour of thermomechanical behaviour of carbon–phenolic and carbon–carbon composites, II. Results. *J Compos Mater* 1992;26:230–55.
- [110] Dimitrienko YI. Thermal stresses and heat-mass-transfer in ablating composite materials. *Int J Heat Mass Transfer* 1995;38:139–46.
- [111] Dimitrienko YI. Thermomechanical behaviour of composite materials and structures under high temperatures: 1. Materials. *Composites* 1997;28A:453–61.
- [112] Milke J, Vizzini AJ. Thermal response of fire-exposed composites. *J Compos Technol Res* 1991;13:145–51.
- [113] Gibson AG, Wu Y-S, Chandler HW, Wilcox JAD, Bettess P. A model for the thermal performance of thick composite laminates in hydrocarbon fires. *Rev L'Inst Franc Petrol* 1995;50:69–74.
- [114] Chen L, Luo C, Lua J, Shi J. A direct coupling approach for fire and composite structure interaction. In: Proceedings of the 17th international conference on composite materials, 27–31 July 2009, Edinburgh, UK; 2009.
- [115] Asaro RJ, Dao M, Schultz M. Fire protection techniques of commercial vessels: structural fire protection modelling. *Flame Retard Poly* 1998:113–27.
- [116] Gibson AG. Unpublished data.
- [117] Springer G, Tsai S. Thermal conductivity of unidirectional materials. *J Compos Mater* 1967;1:166–73.
- [118] Progelhof RC, Throne JL, Ruetsch RR. Methods for predicting the thermal conductivity of composite systems: a review. *Poly Eng Sci* 1976;16:9.
- [119] Han L, Cosner A. Effective thermal conductivities of fibrous composites. *J Heat Transfer* 1981;103:387–92.
- [120] Ott HJ. Thermal conductivity of composite materials. *Plast Rub Proc Appl* 1981;1:9–24.
- [121] Fanucci JP. Thermal response of radiantly heated kevlar and graphite/epoxy composites. *J Compos Mater* 1987;21:129–39.
- [122] James B, Wostenholm G, Keen G, McIvor S. Prediction and measurement of the thermal conductivity of composite materials. *J Phys D: Appl Phys* 1987;3:416–22.
- [123] Havis C, Peterson G, Fletcher L. Predicting the thermal conductivity and temperature distribution in aligned fiber composites. *J Thermophys* 1989;3:416–22.
- [124] Gawayed Y, Hwang JC, Chapman D. Thermal conductivity of textile composites with arbitrary preform structures. *J Compos Technol Res* 1995;17:56–62.
- [125] Tai H. Equivalent thermal conductivity of two- and three-dimensional orthogonally fiber-reinforced composites in one-dimensional heat flow. *J Compos Technol Res* 1996;18:221–7.
- [126] Kalagiannakis G, Van Hemelrijck D, Van Assche G. Measurements of thermal properties of carbon/epoxy and glass/epoxy using modulated temperature differential scanning calorimetry. *J Compos Mater* 2004;38:163–74.
- [127] Knappe W, Ott H-J, Wagner G. Calculation and measurement of the thermal conductivity of GRP. *Kunststoffe* 1978;68:13.
- [128] Henderson JB, Tant MR. Measurement of thermal and kinetic properties of a glass-filled polymer composite to high temperatures. *High Temp–High Press* 1996;18:17–28.
- [129] Lattimer BY, Ouellette J, Trelles J. Thermal response of composite materials to elevated temperatures. In: Couchman L, Mouritz AP, editors. Modeling of naval composite structures in fire. Acclaim; 2006. p. 1–49.
- [130] Luo C, Desjardin PE. Evaluation of thermal transport properties using a micro-cracking model for woven composite laminates. In: Proceedings of the 17th international conference on composite materials, 27–31 July 2009, Edinburgh, UK; 2009.
- [131] Allison DM, Marchand AJ, Mochat RM. Fire performance of composite materials in ships and offshore structures. *Marine Struct* 1991;4:129–40.
- [132] Kucner LK, McManus HL. Experimental studies of composite laminates damaged by fire. In: Proceedings of the 26th International SAMPE technical conference; 17–20 October 1994. p. 341–53.
- [133] Seggewiss PGB. Properties of fire-damaged polymer matrix composites. In: Proceedings of the 3rd conference on composites in fire, 9–10 September 2003, Newcastle, UK; 2003.
- [134] McManus HL. Prediction of fire damage to composite aircraft structures. In: Proceedings of the 9th international conference on composite materials, Madrid, Spain; July 1993. p. 929–36.
- [135] Boyer GT, Thomas WC. An analytical investigation of charring composites undergoing thermochemical expansion. In: Proceedings of the ASME national heat transfer conference, Denver, Colorado, Paper 85-HT-54; 1985.
- [136] Elmughrabi AE, Robinson M, Gibson AG. Effect of stress on the fire reaction properties of polymer composite laminates. *Polym Degrad Stabil* 2008;93:1877–83.
- [137] Goodrich T, Lattimer BY. Microscopic behavior of composite materials during heating and cooling. In: Proceedings of the 17th international conference on composite materials, 27–31 July 2009, Edinburgh, UK; 2009.
- [138] Ramamurthy H. An experimental investigation into the thermophysical properties of decomposing polymer composites. University of Rhode Island, Kingston; Rhode Island; 1988.
- [139] Zhang Z, Case SW. Finite element modeling for composites exposed to fire. In: Proceedings of the 54th international symposium & exhibition, Baltimore, MD; 2009.
- [140] Asp LE. The effects of moisture and temperature on the interlaminar delamination toughness of a carbon/epoxy composite. *Compos Sci Technol* 1998;58:967–77.
- [141] Sjogren A, Asp LE. Effects of temperature on delamination growth in a carbon/epoxy composite under fatigue loading. *Int J Fatigue* 2002;24:179–84.
- [142] Frassine R, Pavan A. Viscoelastic effects on the interlaminar fracture behaviour of thermoplastic matrix composites: I. Rate and temperature dependence in unidirectional PEI/carbon–fibre laminates. *Compos Sci Technol* 1995;58:193–200.
- [143] Kulcarni AP, Gibson RF. Non-destructive characterisation of effects of temperature and moisture on elastic moduli of vinyl ester resin and E-glass/vinyl ester resin composite. In: Proceedings of the American Society of composites, 18th annual technical conference, Florida, 19–22nd October; 2003.
- [144] Mahieux CA, Reifsnider KL. Property modeling across transition temperatures in polymer matrix composites: part 1: tensile properties. *Polymer* 2001;42:3281–90.
- [145] Mahieux CA, Reifsnider KL. Property modeling across transition temperatures in polymers: application to thermoplastic systems. *J Mater Sci* 2002;37:911–20.
- [146] Budiansky B, Fleck NA. Compressive failure of fiber composites. *J Mech Phys Solids* 1993;41:183–211.
- [147] Vaidya UK, Ulven CA, Pillay S, Comstock D. Post-fire impact response of VARTM glass/vinyl ester balsa core sandwich composites. In: ONR solid mechanics program review, marine composites and sandwich structures, 24–26 March 2004, Adelphi, MD; 2004.
- [148] Seggewiss PGB. Methods to evaluate the fire resistance of carbon fiber reinforced plastics. In: Proceedings of the 60th SAMPE symposium & technical exhibition, Long Beach, CA; 2004.