Chapter 6
Structural Behaviour of Composite Materials in Fire

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6.1 Introduction

Fire is a serious safety issue when it comes to a structural component of a civilian building, offshore platform, naval ships or an aircraft that carries high numbers of passengers. At present, many structural components mentioned above is being replaced from a conventional material to an advanced material such as fibre reinforced polymer composites that exhibit superior performance compared to traditional materials. Some common type of high-temperature resin used in composite structures are polyimides, bezoxazines, bismaleimides and cyanate esters. In aerospace application, the combination of carbon fibre and bismaleimide matrix is material of choice for jet engines due to the excellent fire performance. Fire performance is considered as one of the most significant factors in restricting the broader use of composite materials for structural applications. Despite their superior performance compared to other materials such as steel, aluminium or reinforced concrete, composite materials are reactive at high temperatures, particularly for organic matrix and fibres. Composite materials decompose and release heat and smoke when exposed to high temperature and fire environment. The exposure of composite material structures to high temperatures leads to decomposition, associated with thermal and mechanical properties degradation. The degradation causes a reduction in mechanical performances, which is the primary concern in safety aspects.

When a composite material is exposed to fire or heat at a temperature around 300 to 400 °C, the organic matrix decomposes and releasing heat, smoke, soot and toxic volatiles (Mouritz and Gibson 2006). Similar to an organic matrix, organic fibres will also decompose and generate heat, fumes and smoke. Fire scenarios are very complex and different depending on many factors. Figure 6.1 gives an overview of

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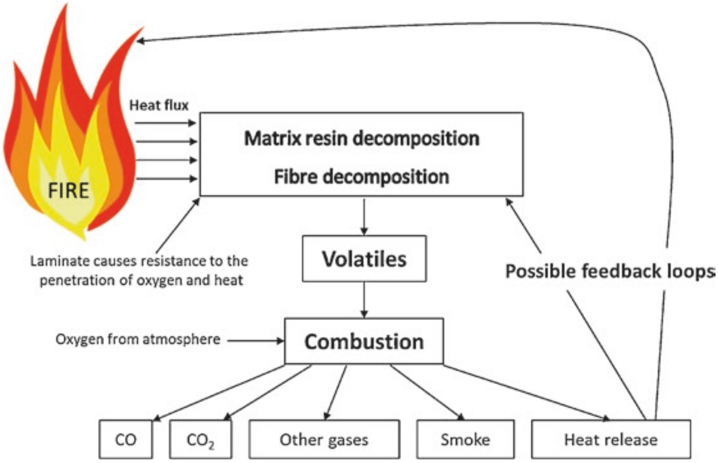

Fig. 6.1 Processes in a fire scenario (A.P. Mouritz and Gibson 2006)

the fire scenario and the mechanism involved in the thermal decomposition of composite materials with possible additional feedback into the composites due to the local burning of decomposition products. The product of decomposition gives feedback into the centre of the fire and will affect the burning intensity.

Figure 6.2 shows the processes occurring in a composite laminate subjected to fire. The process involved when composite laminates receive heat/fire are thermal, chemical, physical as well as the influence in failure modes (Mouritz et al. 2009). The thermal process involved heat conduction, heat generation or absorption by decomposition reaction and convective heat loss from the egress of hot reaction gases and moisture vapours from the composite into the fire. The chemical processes include thermal softening, melting, pyrolysis and volatilisation of the polymer matrix, organic fibres and core material together with the formation, growth and oxidation of char. The physical processes involve thermal expansion and contraction, internal pressure build-up due to the formation of volatile gases and vaporisation of moisture; thermally-induced strains; delamination damage; matrix cracking; surface ablation; and softening, melting and fusion of fibres. The failure modes depend 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. Some of the failure modes experienced by composite laminates include matrix decomposition, pore formation, delamination cracking, matrix cracking, fibre–matrix debonding, and char formation.

The reduction to the structural properties of composite materials due to heat and fire requires an in-depth understanding of the thermal, chemical, physical, softening and failure mechanism. It is crucial to understand the process involved as well as their interactions in analysing the structural behaviour of composites in a fire. The fire reaction properties that define the flammability and fire hazard of polymer composites are described in the next section. Some of the reaction properties include

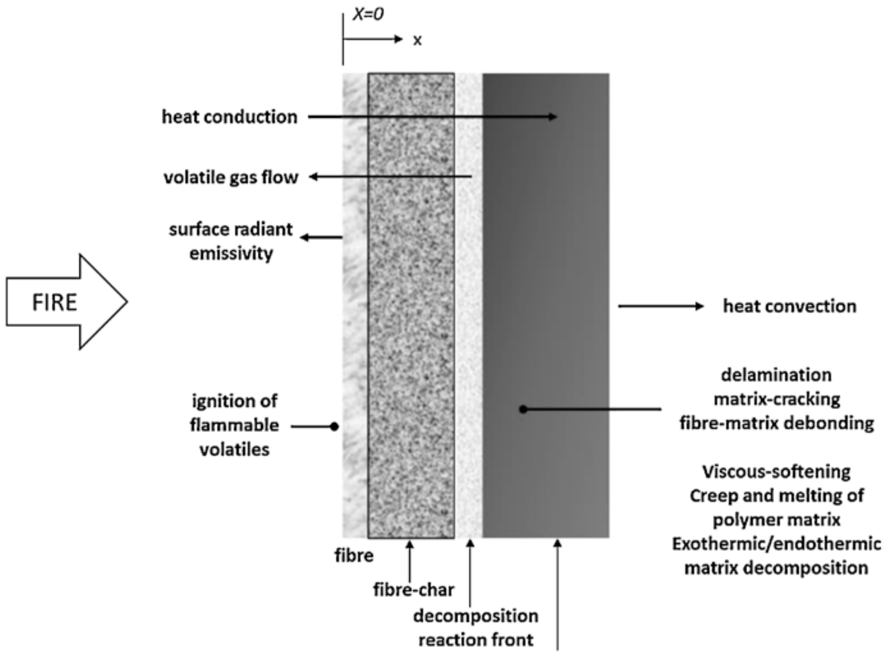

Fig. 6.2 Reaction processes of laminates exposed to fire (Mouritz et al. 2009)

time-to-ignition, heat release rate, flame spread, smoke and gaseous combustion products. The fire resistive properties of composites, such as burn-through rate and mechanical integrity during and after fire, are also described in the next section of this chapter. Overall, this chapter summarises the understanding and key issues on the structural behaviour of composite materials at high temperature and in fire environment. It is envisaged that the understanding of the fire behaviour and mechanisms will increase the fire safety criteria of existing and future application of composite structures.

6.2 Fire Reaction and Resistance Properties of Composites

Fire reaction and fire resistance capability of a material play a significant role in the safety of the structures and personnel in case of fire. Fire reaction properties influence the initiation, growth and spread of fire and determine the survival of humans exposed to fire. Fire resistance measures the ability of a structure to prevent heat transmission and determine structural integrity. In this section, both fire reaction and fire resistance properties are adequately presented.

In the field of fire sciences, fire reaction is a general term that defines the flammability and combustion properties of composite materials. Some of the most critical fire reaction properties are time-to-ignition, heat release rate, peak heat release rate, smoke density, limiting oxygen index, and flame spread rate (Anjang et al. 2014). The heat release rate is being classified as the most critical fire reaction property because it indicates the fire hazard of combustible material (Mouritz et al. 2006). The heat release rate is a quantitative measure of the amount of thermal energy released by a material per unit area when exposed to a fire that radiates a constant heat flux or temperature. The heat release rate value of composite material is not constant but varies with fire exposure times. The value of the heat release rate is determined by the thermal energy released in thermo-chemical decomposition processes. Time-to-ignition is the minimum period required for a combustible material to promote ignition and continuos flaming due to a constant radiant heat flux. The ignition time is used as an approximate measure of the flammability resistance of a material. In high fire risk application, it is very sensible to use materials with longer ignition times. The flame spread rate describes the speed of propagation at which the flame front travels over the surface of combustible material. The flame spread rate is an experimentally measured value and cannot be directly determined. Oxygen index is defined as the minimum oxygen content in the fire environment required to sustain flaming combustion of a material. Materials with high oxygen index values are used in high fire risk applications due to the potential behaviour for self-extinguishing. Two other crucial fire reaction properties are smoke density and gas toxicity. Both properties exhibit a significant impact on the ability of humans to survive in a fire incident. Most fatalities are not triggered by heat and flame but are due to smoke that caused confusion and disorientation that has slow the escape process from the fire incident. As the exposure time to toxic fumes increases, the fire incident may lead to incapacitation and fatalities. The fire reaction properties of composite materials have been characterised, and a wealth of reaction data for different fire or heat flux conditions has been published (Allison et al. 1991; Mouritz et al. 2006; Scudamore 1994; Tewarson and Macaione 1993; Egglestone and Turley (1994); Grenier et al. (1998); Mouritz et al. (2009)).

Fire resistance describes the burn-through resistance and mechanical integrity of a loaded material or structure during and after fire exposure. Resistance to fire also defines the ability of a material or structure to limit the spread of fire from room to room. These fire parameters can be evaluated using small, intermediate or full-scale test methods. These tests can provide information on the mechanical integrity and burn-through resistance of the composites design for a specific fire test condition. However, the tests are complicated to perform, time-consuming, involved high cost and only provide information on the specific case of fire test condition. Fire resistance also describes the physical and mechanical resistance of materials to fire attack. Fire resistance is critical to the safe use of load-bearing composites in aircraft, ships and buildings as their structures may collapse or fail due to losses in strength, stiffness and creep resistance. Several tests are used to determine fire resistance properties, where the furnace and burn-through fire tests are the most notable test. When evaluating the fire resistance of composite structures by using furnace method, controlled heating and realistic fire conditions can easily be achieved. However, the method has some deficiencies that can affect the reliability of the test results; variable results between different furnaces and testing organisations, even though all technically comply with the requirements of the standards. It is also compelling to note that only a relatively small number of tests are suitable for determining the fire reaction properties of composite materials or structures (Mouritz, 2003a; Mouritz and Gibson 2006). When discussing the fire resistance capability, it is interesting to contemplate on the effect of simultaneous heating and loading that is exposed to a composites material or structure. A large amount of experimental data on the fire resistance of composite laminates has been obtained, particularly for fibreglass reinforced polymer laminates and sandwich composites (Allison et al. 1991; Anjang et al. 2014; Bai and Keller 2009; Feih et al. 2007b; Feih and Mouritz 2012; Gibson et al. 2012; Gibson et al. 2010; Luo et al. 2012; Marquis et al. 2013; Summers et al. 2012a). More information on the behaviour of the materials under simultaneous heating and loading is thoroughly discussed in the next sections of the chapter.

At present, there is no single test or experimental method that are adequate in evaluating all the fire properties of a composite. Two or more methods is necessary to obtain a complete understanding of the fire reaction and resistance behaviour of a composite.

6.3 Thermal Response of Composite Materials

Composite materials that are exposed to sufficiently high heat flux radiated from the fire or due to the high temperature environment will thermally decompose and yield gaseous, chars and smokes. The thermal response of composite materials due to heat exposure or fire environment is a temperature-dependent process (Mouritz et al. 2009). Figure 6.3 summarised the approximate temperatures on the different processes that occurred in a composite material. The first event that occurs when composite material is exposed to high temperature and fire is heat conduction. The heat conduction is governed by the incident heat flux and thermal diffusivity of the virgin composite material. The heat conduction through composite material is complicated due to the highly anisotropic nature of the thermal properties. The rate of heat conduction along the fibre direction is much faster compared to the through-thickness direction. The situation is further complicated as the thermal conductivity, and the specific heat of composite materials vary with temperature.

The heat conduction will expand and contract the composite materials specimen or structure depending on the temperature. The amount of contraction and expansion on the polymer matrix below the glass transition temperature, T_g is determined by the thermal expansion linear coefficient of the virgin material. Thermal gradient in the through-thickness direction is non-uniform; highest at the hot surface and lowest at the cold face (Pei Gu and Chen 2012). Some types of fibre display anisotropic thermal conductivity behaviour, where when the material is heated, both contraction and expansion coincided. As an example, carbon fibre will expand in the

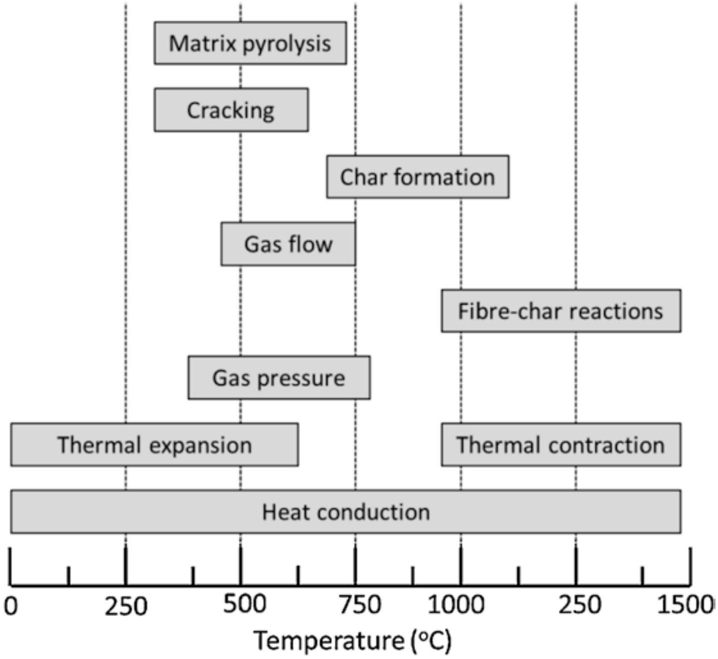

Fig. 6.3 Different processes and temperature (Mouritz et al. 2009)

through-thickness direction and contract slightly in the axial (or fibre) direction when heated.

Below the decomposition temperature of a polymer matrix, heat energy is transferred via conduction, where a small amount of energy is absorbed in the thermal expansion. Composite materials begin to decompose at sufficiently high temperature. Typically, the decomposition temperature of a polymer matrix is in the range of 250° to 350 °C depending on the composition and chemical stability of the organic material, heating rate as well as the fire atmosphere (Rahman and Kumarasamy 2017). In the physical process where contraction and expansion involved, internal pressure rise and build-up due to the formation of volatile gases; vaporisation of moisture; thermally-induced strains; delamination damage; matrix cracking; surface ablation; and softening, melting and fusion of fibres. These processes occur concurrently, and this enumerates to the complexity of fire behaviour. The pressure exerted by the gas culminates pores formation, delamination and matrix cracking. When the matrix has becomes sufficiently porous, and crack is noticeable, the volatile gases and water vapour flow through the degraded region into the heat or fire environment. This has a convective cooling effect which reduced the heat conduction. The pyrolysis gas will also cool the composite depending on the heat capacity of the gases.

For the organic matrix and fibre, the endothermic decomposition process continues until the reaction zone reaches to the back face of the composite laminates. The combustible matrix and fibre are then finally degraded to volatiles and chars. At this phase, the decomposition process ends unless a sufficiently high temperature that instigates pyrolysis reactions between the fibres and char. In the case of glass fibres where the temperature exceeds ~1000 °C, the char retaliate with the silica network resulting in a substantial mass loss. For carbon fibre composites, the fibres and chars were oxidised due to the oxygen-rich environment during fire (Feih and Mouritz 2012).

In summary, many processes involved when composite materials are exposed to fire. The overall process is very complex depending on the fire scenarios as well as due to the different types of composite materials involved in the scenario. The processes also do not occur in separation from each other. The complexity of the process is further cumbersome due to the anisotropic properties and the temperature-dependent properties of composites. It is also essential to understand the sequence of events that occur when composite material is exposed to high temperature and fire environment.

6.4 Fire Structural Behaviour Under Loading

The mechanical responses such as strength, stress, strain and displacement of composites under elevated temperatures and fire environments are significantly affected by their thermal exposure (Bai and Keller 2009). Contrarily, mechanical responses have almost no influence on the thermal responses of these materials. As a result, the mechanical and thermal responses can be dissociated from each other. Structural fire behaviour under loading considers both thermal and mechanical response. Significant advances have been made in the modelling and testing of the structural response of composite materials in fire. Thermal-mechanical models have been developed to predict temperature rise, softening rate, residual stiffness and strength, and failure stress and failure time of composites at elevated temperature or in fire (Asaro et al. 2009; Bai and Keller 2009; Yu Bai et al. 2008; Birman et al. 2006; Dimitrienko 1997; Gu 2012; Liu et al. 2011; Luo et al. 2012; Mouritz et al. 2009; Nguyen et al. 2019; Sullivan 1993; Summers et al. 2012b; Tran et al. 2018). A large amount of experimental data on the fire resistance of composites has also been obtained, particularly for fibreglass reinforced polymer laminates (Anjang et al. 2014; Anjang et al. 2017; Elmughrabi et al. 2008; Feih et al. 2007a,b; Feih et al. 2007; Gibson et al. 2010; Wang et al. 2014). This section provides a review of the structural fire behaviour under tensile and compressive loading.

Substantial progress has been made in the development of finite element and analytical models to investigate the compressive structural integrity of composites in fire (Bhat et al. 2017; Birman et al. 2006; Pei Gu and Asaro 2008; Pei Gu and Chen 2012; Krysl et al. 2004; Looyeh and P. Bettess 2001). Modelling the structural response of composites in predicting their fire behaviour under compression loading is less complicated because the fibre reinforcement is not significant in controlling softening and failure. The initial step in analysing the compression properties is the calculation of the temperature distribution through the composite with increasing time using the thermal model. By using the through-thickness temperature distribution, the reduction to the mechanical properties can be calculated. Currently, the reduction to the mechanical properties with increasing temperature must be measured experimentally at elevated temperature under isothermal conditions. The compression model assumes that the mechanical properties of the composites decrease via a single-stage (rigid-to-rubbery) glass transition of the polymer matrix with increasing temperature. The compression strength of most composite laminates decreases with increasing temperature, as depicted in Fig. 6.4.

The simplest method to assess the fire structural behaviour under loading is by performing a small-scale test set up (stress-rupture test). Although the full-scale fire test is generally required in displaying the realistic condition, the small-scale fire test is adequate to predict the fire resistance capability of a structure under loading (Mouritz and Gibson 2006). Many researchers have investigated the fire structural survivability of composites under combined compressive loading and one-sided heating (Bhat et al. 2017; Boyd et al. 2007; Feih et al. 2008; Pei Gu and Asaro 2012; Liu et al. 2011). Studies on the reduction to the mechanical properties of composite materials due to combined heating and compressive loading have unveiled that compressive creep failure occurs at temperatures around the glass transition temperature of the polymer matrix, within the range of 100–180 °C (Boyd et al. 2007; Feih et al. 2007a). At higher temperatures, failure is also dependent on the decomposition and the matrix delamination cracking (Gibson et al. 2006; Liu et al. 2011). The experiment revealed that time-to-failure values decreased with increasing heat flux (temperature) and applied compressive stress (Feih et al. 2007a; Feih et al. 2008; Kim et al. 2007). The thermo-mechanical model used in calculating the

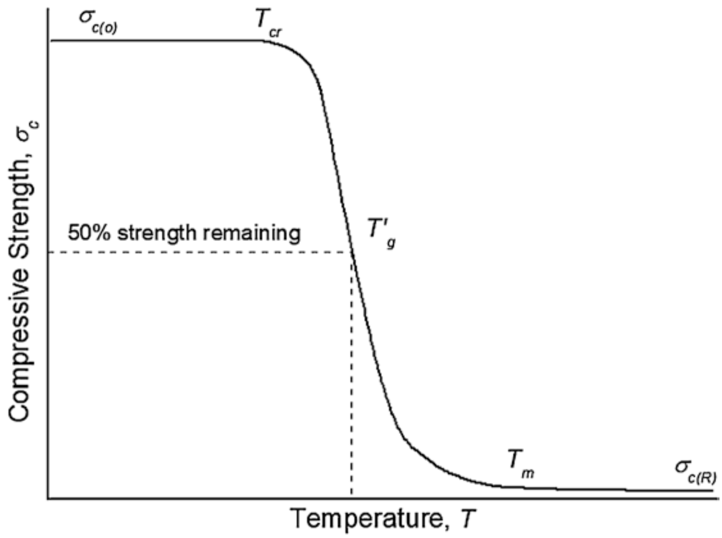

Fig. 6.4 Typical relationship between temperature and compressive strength (Feih et al. 2008)

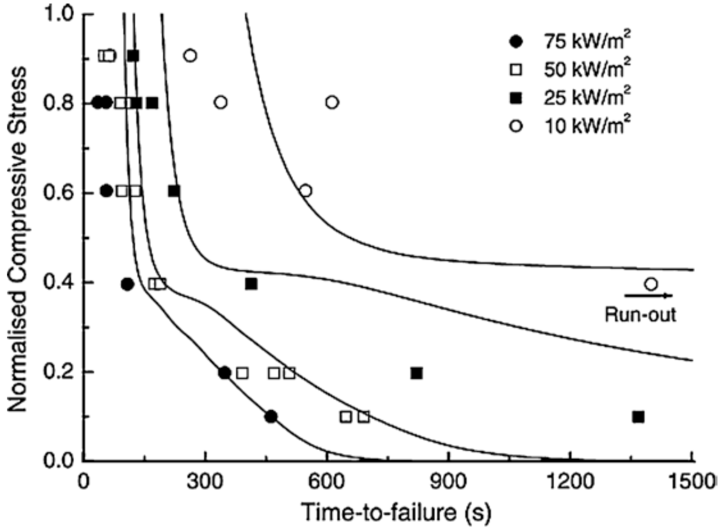

Fig. 6.5 Failure times of the composite laminate tested at different heat fluxes (Feih et al. 2007a)

time-to-failure of laminates supporting a static compressive stress during one-sided heating able to predict the experiment with reasonable accuracy as depicted in Fig. 6.5.

The thermal-mechanical model developed by Feih (Feih et al. 2008) also able to calculate with reasonable accuracy the failure times of sandwich composites consisting of E-glass/vinyl ester and balsa core. The model predicts that the time-to-failure increases with the skin thickness and when the applied compressive stress or heat flux is reduced as depicted in Fig. 6.6. Nevertheless, the model was not able to accurately predict the failure time for all heat flux conditions due to the complexity of the failure process of the face skins of the sandwich. The model is accurate when all plies in the front skin fail at the same time due to microbuckling, which occurs under high heat flux and high stress conditions. Extensive amounts of research on the development of thermal-mechanical models for calculating the fire structural response and failure of composites under compression load models only assume that the weakening of the composite is solely due to matrix softening (Boyd et al. 2007; Pei Gu and Asaro 2008, 2012; Lattimer et al. 2004; Lua et al. 2006). Other softening processes such as pore formation and delamination are not considered into their mechanical models. Further analysis and validation are needed to incorporate damage and failure processes into the thermal-compressive mechanical models. The accuracy of the newly developed model also needs to be determined against experimental data for a wide variety of composite materials.

The behaviour of composites in fire under tensile loading is different and more complicated than compression loading. In analysing the tensile response, both matrix and fibre softening effects need to be considered and analysed. Several models have been developed to calculate the tensile softening and failure of composites

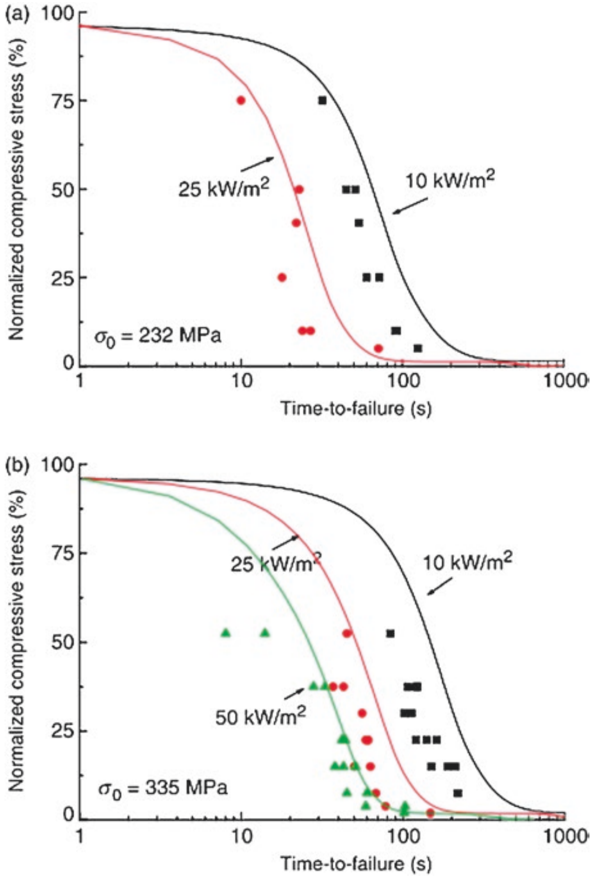

Fig. 6.6 Failure times of sandwich composites under combined compression and one-sided heating at different heat fluxes (**a**) 2 mm skin thickness and (**b**) 5 mm skin thickness (solid curve: prediction, data points: experimental) (Feih et al. 2008)

in fire (Anjang et al. 2014, 2017; Bhat et al. 2015; Elmughrabi et al. 2008; Feih et al. 2007; Pering et al. 1985). Similar to the compression model, tension model takes into account both thermal-mechanical response into the fire behaviour (stress rupture) analysis. The loss in tensile strength of the fibreglass with increasing temperature is much more gradual than the loss in compressive strength of the polymer matrix, and this accounts for the laminate having longer failure times under tensile loading. Figure 6.7 gives the time-to-failure of a woven glass/vinyl ester composite under tension and compression loading when being exposed with similar heat flux level. The failure times for tension loading is about an order of magnitude longer than for a compression loading. Failure of the laminate under tension loading involved the decomposition of the polymer matrix and is later controlled by creep rupture of the fibres, whereas under compression the process is strongly influenced by thermal softening of the polymer matrix.

Similar to compression, the tensile strength of most polymer laminate decrease with increasing temperature as depicted in Fig. 6.8. In analysing fire under tensile loading, fibre strength loss is regarded as both time and temperature-dependent.

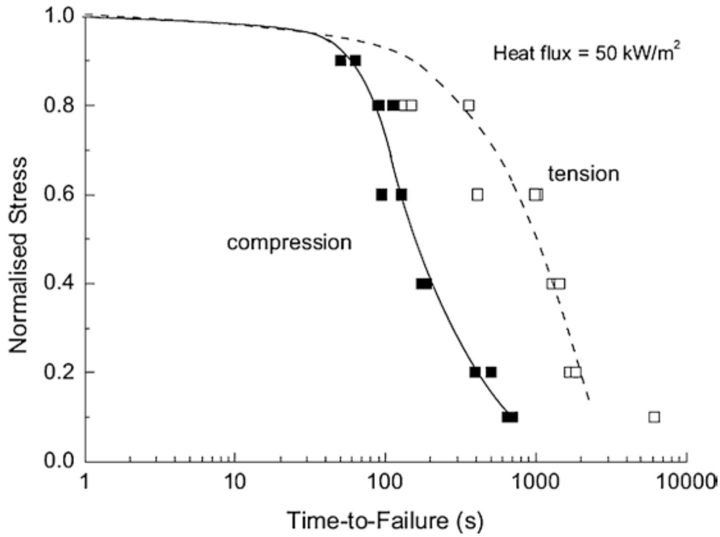

Fig. 6.7 Comparison of the time-to-failure of a glass/vinyl ester laminate under tension and compression at a heat flux of 50 kW/m^2 (Feih et al. 2007b)

Fig. 6.8 Relationship between temperature and tensile strength of a polymer (Feih et al. 2007)

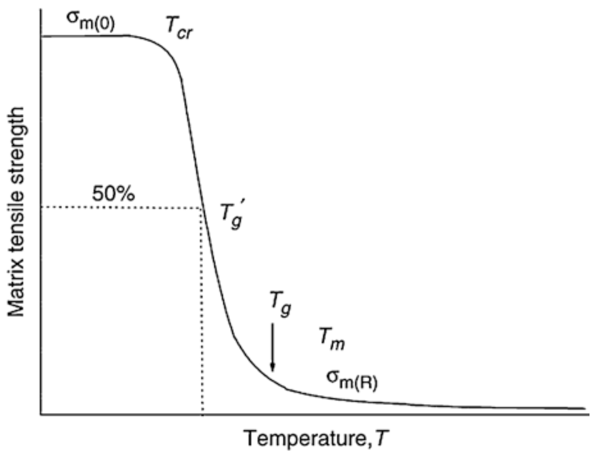

Figure 6.9 shows the effect of temperature and heating time on the normalised tensile strength of E-glass bundles. The tensile strength of the fibre bundles decreases with increasing temperature and heating time. Details on the equation used to model the thermal-mechanical response will not be discussed in this chapter. A comprehensive explanation of the model can be found written by Feih et al. (2007). Only types of fire model to predict the failure behaviour will be discussed and the validation with experimental fire test are shown.

The average strength model developed by Feih et al. (2007) and Gibson et al. (2006) as shown in Fig. 6.10 can predict the failure stresses and times of fibreglass

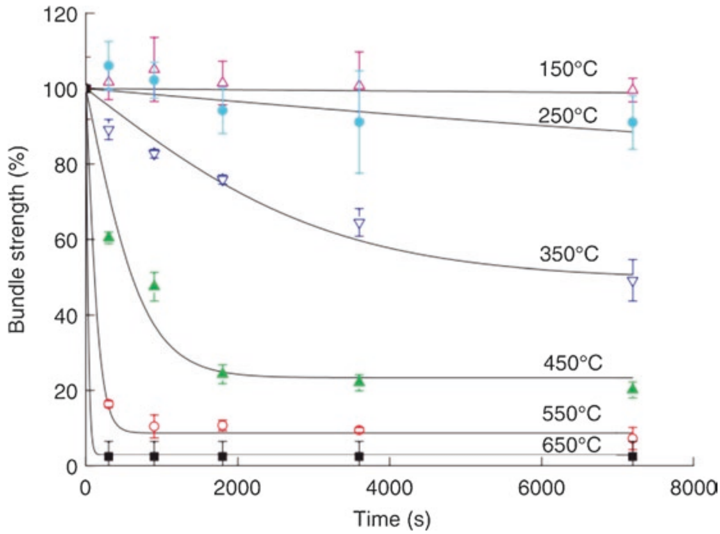

Fig. 6.9 Fibre strength as a function of time and temperature (Feih et al. 2007)

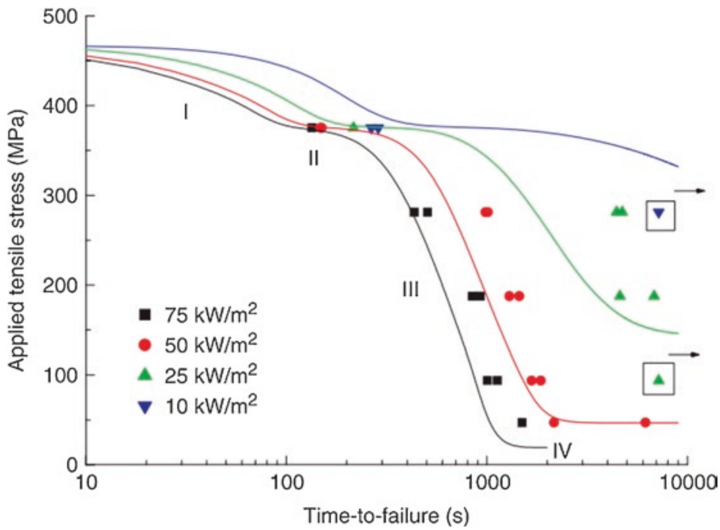

Fig. 6.10 Comparison of failure times calculated using average strength model for a glass-vinyl ester laminate at different heat fluxes (Feih et al. 2007)

laminates with good accuracy. This tension model does not analyse all the damage processes which control the mechanical properties and failure such as thermal strain, pore formation, delamination and fibre-matrix debonding however the model gives a good estimation of tensile strength and failure time of E-glass/vinyl ester composite. Another model by Gibson et al. (Gibson et al. 2006) has shown that the

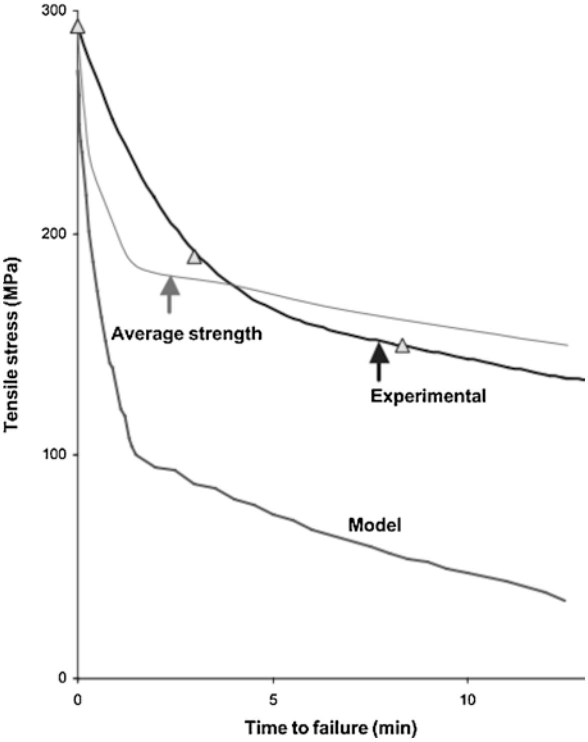

Fig. 6.11 Time-to-failure prediction for glass/polyester laminate (Gibson et al. 2006)

thermal model, coupled to laminate theory, can give reasonable predictions for mechanical behaviour under load. The thermal model, coupled to this laminate theory is from previous analysis that predicts the evolution of temperature and resin decomposition with time through-the-thickness of the laminate. Figure 6.11 gives the failure curve calculated using the average strength model on a glass/polyester composite. Model to analyse the tensile response of sandwich composites exposed to fire is also capable to determine the temperature rise, tensile failure stress and failure mechanism of the sandwich (Anjang et al. 2014; Anjang et al. 2017). Although the above mentioned model able to calculate with reasonable accuracy of the fire structural behaviour, further development is required to incorporate damage modelling (cracks and other damage) into the thermal–mechanical model.

6.5 Post-Fire Behaviour of Composite Materials

The post-fire behaviour is essential to evaluate the structural integrity and safety of heat-affected composite materials following a fire. The polymer matrix used in the composite materials will decompose, ignite and burn due to the exposure to high temperature or fire. Inadequate fire protection will result in rapid ignition to the composite structures that release large amounts of heat, smoke and potentially toxic fumes (Anjang et al. 2015; Gardiner et al. 2004; Mouritz and Gardiner 2002; Sorathia et al. 1993). After a fire is extinguished, it is vital to analyse the post-fire properties in order to assess the residual integrity and safety of the composite structures. The residual mechanical properties of composite following fire can be significantly reduced due to the decomposition and damage of the polymer matrix (Mouritz and Mathys 1999, 2000, 2001). Mouritz and Mathys suggested that when a burnt composite is loaded in uniaxial tension at room temperature, the residual tensile properties can be approximated using a rule-of-mixtures model. In the model, the post-fire properties are determined by combining the tensile properties of the unburnt and char regions using a rule-of-mixture formulation to give the bulk post-fire strength and stiffness of the fire-damaged composite. Figure 6.12 shows a schematic of fire damage in a laminate which forms the basis of the model.

The post-fire models have been validated for several types of laminates and sandwich composites (Gardiner et al. 2004; Gibson et al. 2004; Mouritz, 2002; Mouritz and Gardiner 2002; Z Mathys et al. 2002). Figure 6.13 shows one example of a successful validation of the post-fire tensile strength and stiffness of a woven glass/polyester laminate. The post-fire properties decrease with increasing heating time, and the agreement between the calculated and measured post-fire properties is excellent. The reduction is due to the thermal degradation of the polymer matrix that forms a weak char region. Figure 6.14 gives the validation of the post-fire properties for sandwich composites. The model reveals that the post-fire tension properties are controlled by char damage to the entire sandwich. Different from post-fire tension, post-fire compression shows more significant degradation. This difference occurs because softening and failure of the composite materials under compression loading are dominated by the front skin (Anjang et al. 2015). The post-fire models are capable of predicting the temperature rise in the composite materials and the resultant reduction to the mechanical properties. The post-fire model also had shown that

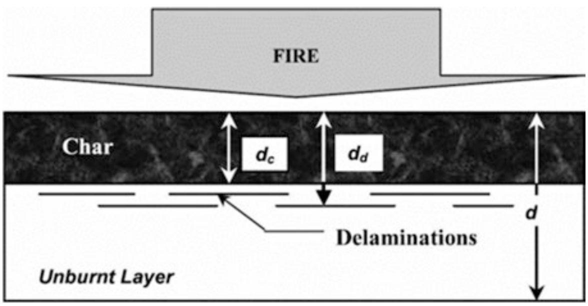

Fig. 6.12 Schematic of fire damage (Mouritz 2002)

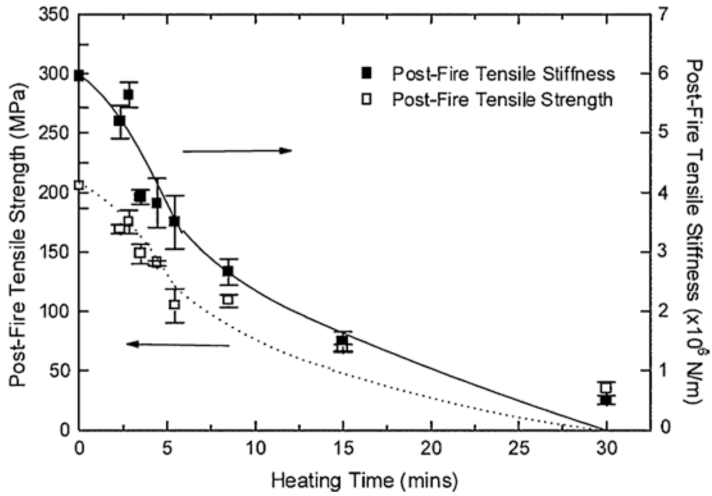

Fig. 6.13 Post-fire tensile strength and stiffness (Mouritz 2003b)

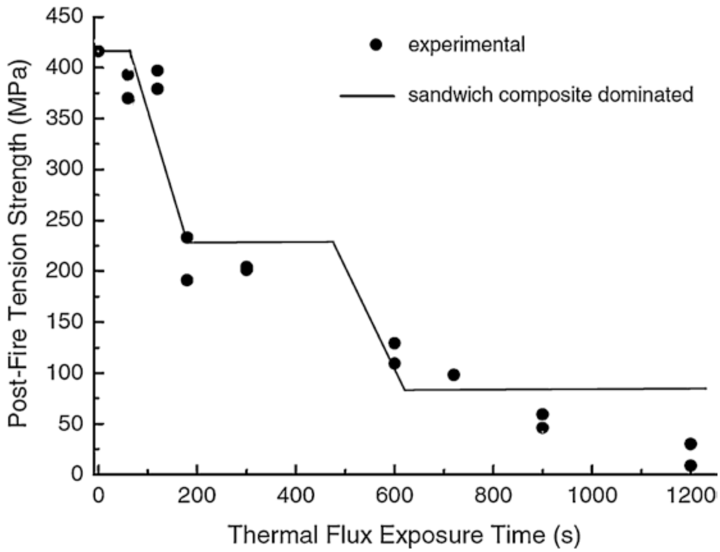

Fig. 6.14 Post-fire tensile properties of sandwich composites (Anjang et al. 2015)

other types of fire-induced damage, such as delamination cracking and overheating of the resin within the unburnt region of the composite, do not have a considerable influence on the post-fire properties (Mouritz et al. 2004).

6.6 Fire Protection for Composite Materials

It has been demonstrated that structural survivability of composite structures depends on the capability of the material in resisting deformation and failure, rather than on eluding from flaming combustion (Mouritz et al. 2009). The protection system is crucial in reducing the risk of fire on composite materials. There are two types of fire protection for composite materials; namely passive and active fire protection. As the thermal softening of the polymer matrix is the dominant process controlling the structural behaviour of composites in high temperature and fire environments; thermal insulation protection is vital to be incorporated into the composite structure. Passive insulation involves fire protecting the composite with a surface coating which has very low thermal conductivity and is thermally inert. Examples of passive insulation materials are cement-based coatings, aggregate gypsum containing cellulosic particulates or glass fibre reinforcement, mineral fibres, and insulations board.

Reactive insulation is different from passive insulation. In reactive insulation, the coatings react when exposed to the fire, which increases their thermal insulation properties. Some reactive coatings release volatiles into the fire, which then reacts against the combustion process. The most common type of reactive insulation is intumescent coating, which is commonly applied onto the substrate as an organic-based paint. Intumescent coatings provide fire protection by undergoing an endothermic decomposition reaction process at an elevated temperature that causes the material to swell and foam into a highly porous, thick and thermally stable char layer (Camino et al. 1989). In recent years, there has been an increasing interest in the application of intumescent coatings due to their advantages, including their ability to form foamed char and produce less smoke and toxic gases during combustion (Jeencham et al. 2014; Rajaei et al. 2017; Wu and Yang 2011).

In summary, whenever fire resistance is required, better fire performance can be obtained by adding the selected protection system in the composites. By having the fire protection system, flame retardancy is enhanced and will reduce the incident that may occur due to fire.

6.7 Conclusion

Studying and understanding the fire behaviour of composite materials is essential in preventing accidents in the many industries that utilising composite materials as the structure or component. This chapter has reviewed the fire reaction and fire resistance properties of composite materials. The thermal response, as well as the effect of loading on the fire behaviour, is also adequately explained. The thermal and mechanical model is essential in predicting the behaviour of the composites at elevated temperature and due to fire exposure. Advancement on the models still needs to be enhanced for better prediction of the fire behaviour. Fire testing; although expensive and cumbersome; also needs to be performed to validate the model further on various types of composites. It is envisaged that by understanding the fire behaviour and mechanisms, the fire safety criteria of existing and future application of composite structures will be surpassed and enhanced.

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