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Post-fire mechanical properties of sandwich composite structures

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ABSTRACT

A thermal–mechanical model for calculating the residual stiffness and strength of fire-exposed sandwich composite structures is presented. The model computes the unsteady-state heat flow and decomposition of a sandwich composite exposed to one-sided radiant heating representative of a fire scenario. The model also computes the residual tension and compression properties of a fire-exposed sandwich composite at room temperature. The accuracy of the model is assessed using post-fire stiffness and failure stress property data for a sandwich composite beam consisting of face skins of E-glass/vinyl ester laminate and a core of balsa wood. Experimental testing reveals that the residual tension and compression properties of the sandwich composite decrease rapidly due mainly to thermal decomposition to the fire-exposed skin. It is demonstrated that the model can accurately predict the residual stiffness and strength properties of fire-exposed sandwich composites. The model reveals that the post-fire tension properties are controlled by char damage to the entire sandwich composite whereas the post-fire compression properties are only dependent on charring to the front skin, resulting in a more rapid loss in stiffness and strength than the tension properties.

1. Introduction

A problem with using sandwich composites in structural applications is poor fire resistance [1]. The polymer matrix to the laminate skins will decompose, ignite and burn when exposed to high temperature fire. Similarly, organic core materials used in sandwich composites (e.g. polymer foam, syntactic foam, Nomex, balsa wood) are flammable. Fire is a major threat to the application of sandwich composites used in aircraft, ships, civil infrastructure, offshore platform and other uses. Without adequate fire protection, sandwich composites can ignite and burn with the release of large amounts of heat (which adds to the fuel load), smoke and potentially toxic fumes [1–4]. Sandwich composites can also weaken and fail due to thermal softening and decomposition of the skins and core. It is a critical safety issue that sandwich structures are designed to survive a specified fire hazard (e.g. ISO834 cellulosic fire or UL1709 hydrocarbon fire conditions) without posing a threat to safety and without excessive back surface heating or failure [2].

Assessing the fire structural performance and survivability of sandwich composites is reliant on modelling and experimental testing. Many models have been developed to predict the thermal–mechanical response of sandwich composites in fire [5–12]. The models consider the case of a flat sandwich panel under combined mechanical loading and one-sided uniform heating representative of fire. The models are capable of predicting the temperature rise in the sandwich composite and the resultant reduction to the mechanical properties. However, the models are only valid for computing the softening and failure of sandwich composite in fire. The models are not valid for heat-exposed sandwich composites whereby the fire has been extinguished and the material has cooled to ambient temperature.

The capability to predict the residual mechanical properties of sandwich composites following fire is needed. Determining the post-fire properties is essential to evaluate the structural integrity and safety of heat-affected sandwich composites following fire. Mouritz and Gardiner [13] developed a model to calculate the post-fire compression stiffness and strength of polymer foam core sandwich composites that fail by either core shear cracking or front skin buckling. The work by Gardiner and Mouritz revealed that the extent of decomposition (char) through the sandwich composite is

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the damage controlling the post-fire compression properties. Ulven and Vaidya [14] experimentally assessed the post-fire impact response of sandwich composite materials. Apart from these two studies, the post-fire mechanical properties of sandwich composites have not been studied. However, there is a large body of modelling and experimental research into the post-fire mechanical properties of fibre reinforced polymer laminates [15–27], which can be relevant to the post-fire properties of the laminate skins to sandwich composites.

This paper presents a thermal–mechanical model for calculating the post-fire properties of sandwich composites. The thermal component of the model computes the heat conduction through the sandwich composite and the resultant thermal decomposition (charring) to the skins and core. The mechanical component calculates the residual stiffness and strength properties of the fire-damaged sandwich composite based on the amount of charring. The accuracy of the model is assessed using post-fire tension and compression property data for a sandwich composite consisting of woven glass/vinyl ester laminate skins and balsa wood core. This material was selected because of its use in naval ship structures such as the superstructure and hull, where ship-board fire is a risk.

2. Post-fire model for sandwich composites

The model to calculate the post-fire mechanical properties involves thermal, decomposition and mechanical analysis of sandwich composites with organic skins and core. The model involves three main analytical steps: (1) thermal analysis, (2) decomposition analysis and (3) post-fire property analysis. The first step involves thermal analysis to calculate the through-thickness temperatures of the sandwich composite when exposed to a one-side thermal flux radiated by fire. The second step involves computing the amount of through-thickness decomposition (char formation) to the skins and core, which is based on the thermal analysis. The final step involves the use of mechanical models to calculate reductions to the post-fire tension and compression properties of the sandwich composite, which is based on the decomposition analysis. It is assumed with the model that the reduction to the post-fire properties is caused solely by char formation.

2.1. Thermal analysis of sandwich composite

Thermal analysis of the sandwich composite exposed to one-sided radiant heating representative of a possible fire scenario is based on the model developed by Henderson et al. [28] for laminates and then adapted for sandwich composites by Feih et al. [29]. A full description of the model is given in Ref. [29], and therefore it is only briefly described here. The thermal analysis assumes that the sandwich composite is uniformly heated over one skin, and heat transfer only occurs in the through-thickness direction (and not in the lateral and transverse directions). The one-dimensional governing equation to calculate the temperature rise with heating time ($\partial T/\partial t$) in the front skin (exposed directly to the fire), core and back skin are calculated using the equations [29]:

$$\text{Skins}: \quad \rho_{(s)} C_{p(s)} \frac{\partial T}{\partial t} = k_{x(s)} \frac{\partial^2 T}{\partial x^2} - \dot{m}_g C_{pg(s)} \frac{\partial T}{\partial x} - \frac{\partial \rho}{\partial t}\left(Q_{(s)} + h_{solid_{(s)}} - h_{gas(s)}\right) \tag{1}$$

$$\text{Core}: \quad \rho_{(c)} C_{p(c)} \frac{\partial T}{\partial t} = k_{x(c)} \frac{\partial^2 T}{\partial x^2} - \dot{m}_g C_{pg(c)} \frac{\partial T}{\partial x} - \frac{\partial \rho}{\partial t}\left(Q_{(c)} + h_{solid_{(c)}} - h_{gas(c)}\right) \tag{2}$$

The subscripts s and c refer to the skin and core, respectively. ρ is the density. k_x and C_p are the through-thickness thermal conductivity and specific heat capacity, respectively. $\dot{m}_g$ is the mass flux of volatiles from the decomposition zone in the sandwich composite towards the fire exposed surface. C_{pg} is the specific heat capacity of volatiles. Q is the endothermic decomposition energy of the skin ($Q_{(s)}$) or core ($Q_{(c)}$). h_{solid} and h_{gas} are the enthalpies of the solid and gas phases, respectively, and are defined as:

$$h_{solid} = \int_{T_\infty}^{T} C_{p(solid)} dT \tag{3}$$

$$h_{gas} = \int_{T_\infty}^{T} C_{p(gas)} dT \tag{4}$$

k_x, $C_{p(solid)}$, $C_{p(gas)}$ and Q must be experimentally determined for the skin and core.

The thermal model is validated in this study using a sandwich composite consisting of woven E-glass/vinyl ester laminate skins and balsa wood core. Lattimer et al. [30] experimentally determined the thermal conductivity of these materials up to about 600 °C, above which all the organic material has completely degraded. The thermal conductivities of the skin and core are defined as a function of temperature using:

$$\text{skin}\begin{cases} k_{x(s)} = 4.405x10^{-5}T + 0.312 & \text{below the matrix decomposition temperature} \quad (5a) \\ k_{x(s)} = 2.83x10^{-4}T + 0.095 & \text{above the matrix decomposition temperature} \quad (5b) \end{cases}$$

$$\text{core}\begin{cases} k_{x(c)} = 9.211x10^{8}T^{2.503} + 0.06 & \text{below the balsa decomposition temperature} \quad (6a) \\ k_{x(c)} = 2.223x10^{6}T^{2.503} + 0.0008 & \text{above the balsa decomposition temperature} \quad (6b) \end{cases}$$

Lattimer et al. [30] have also determined the empirical relationship between specific heat capacity and temperature for the skin and balsa:

$$\text{skin}\begin{cases} C_{p(s)} = 0.0452T + 1080 & \text{below the matrix decomposition temperature} \quad (7a) \\ C_{p(s)} = 0.259T + 1041 & \text{above the matrix decomposition temperature} \quad (7b) \end{cases}$$

$$\text{core}\begin{cases} C_{p(c)} = 0.68T + 1420 & \text{below the balsa decomposition temperature} \quad (8a) \\ C_{p(c)} = 1.33T + 3194 & \text{above the balsa decomposition temperature} \quad (8b) \end{cases}$$

The specific heat capacities of gases evolved from the polymer matrix to the skins and the balsa core are dependent on the temperature according to [30]:

$$\text{Skin} \quad C_{pg(s)} = -91.151 + 4.400T - 1.7279 \times 10^{-3}T^2 \tag{9a}$$

$$\text{core} \quad C_{pg(c)} = 299.8 + 5.4037T - 1.60 \times 10^{-3}T^2 \tag{9b}$$

The thermal model makes several important assumptions about the thermal behaviour of a sandwich composite in fire. Firstly, the model is a one-dimensional equation that only analyses conductive heat transfer and mass transport of decomposition gases in the through-thickness direction. Heat conduction and gas flow in the lateral and transverse directions of the sandwich composite are assumed not to occur because the material is evenly heated over one surface. Secondly, it is assumed that heat-induced delaminations, skin-core interfacial cracking and other types of damage to the sandwich composite do not alter the thermal conductivity or gas flow. It is also assumed that the temperature is only dependent on heat conduction, gas flow and decomposition, and other processes (e.g. internal pressures, thermal-induced or force-induced strains) have no affect.

The thermal boundary condition on the hot skin is assumed to be a constant thermal flux. The model can consider any thermal boundary condition for the back skin surface. In this study the back skin is assumed to be partially insulated.