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Deterioration of the fire structural resistance of sandwich composite under tension due to water absorption

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ABSTRACT

The effect of water absorption on the fire structural resistance of a sandwich composite is investigated. A sandwich material consisting of E-glass/vinyl ester laminate skins and balsa wood core was environmentally aged in hot (70 °C) and humid (85% relative humidity) conditions for an increasing period up to and exceeding the saturation time. The face skins displayed Fickian diffusion behaviour in the absorption of water whereas the core exhibited significant mass loss due to water causing hydrolysis of bioorganic compounds in the wood. Water absorption decreased the fire structural resistance of the sandwich composite under tensile loading. The saturated sandwich composite exposed to fire failed at lower tensile stresses and within shorter times compared to the dry composite. The reduction in fire resistance was primarily due to moisture-induced weakening of the laminate skins. The reduction to the fire structural resistance caused by water absorption was predicted using a thermal–mechanical model.

1. Introduction

The absorption of water by fibre-reinforced polymer laminates and sandwich composites can be a significant problem when used in wet environments. A majority of structural applications of laminates and sandwich composites, including aerospace, automotive, marine, civil infrastructure, buildings and pipes, involve exposure to water in the forms of humidity, rain, or partial/complete immersion in water, seawater or water-based fluid (e.g. slurry).

The effect of water absorption on the physical and mechanical properties of many types of laminates [1–11] and sandwich composites [12–17] has been studied for a range of environmental conditions, and in particular water immersion and hot–wet exposure. Water absorbed by the polymer matrix in laminates exists as both free water (H_2O molecules located within the free spaces between the polymer chains) and bound water (H_2O molecules bound to the molecular network via hydrogen bonds) [18,19]. The absorbed water can plasticize and/or chemically break-down some polymers, soften the fibre–matrix interface, and weaken the fibres [1–11]. This damage can reduce the mechanical properties of laminates, depending on the types of fibre reinforcement and polymer matrix. Similarly, water absorbed into the organic core (e.g. polymer foam, Nomex, balsa) of sandwich materials exists in both the free and bound forms. This water can cause swelling and reduce the mechanical properties of wood, which is often used as a core material [20–22]. Absorbed water can reduce the mechanical properties of sandwich composites via weakening of the skins, core, and skin-core interface [12–17].

While the effect of water absorption on the mechanical properties of many types of structural composite materials is well known, it is not known whether absorbed water also affects their fire structural resistance. In the context of this study, fire resistance defines the capacity of a load-bearing composite material to maintain structural integrity when exposed to fire. Composites are often used in applications where both water/moisture exposure and fire events can occur, such as for ships and offshore drilling platforms. Many studies have assessed the structural response and survivability of laminates and sandwich composites exposed to fire [23–33], although in all cases the materials tested were in a dry condition. It is therefore not known whether the fire structural integrity of composites is affected by water absorption. Feih et al. [34] studied the effect of retained water in phenolic matrix laminates on the fire structural performance. The water is produced as a by-product of the phenolic cure reaction, and most likely occurs as both free and chemically bound water. When water was present at high

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concentration it caused 'explosive-type' delamination cracking in the phenolic laminate during fire exposure. The water within the phenolic vaporized at the high temperature, which generated a high internal pressure that caused extensive delamination cracking and reduced the fire structural resistance of the phenolic laminate. Apart from this study by Feih and colleagues [34], the effect of water on the fire structural resistance of composite materials has not been studied and is not well understood.

The aim of this study is to determine whether the fire structural resistance of a sandwich composite material used in marine and civil structures is affected by absorbed water. The study explores whether absorption of water by the skins and core changes the thermal response, deformation and softening rates, and structural survivability of the sandwich material exposed to fire. The sandwich composite investigated in this study is compromised of woven E-glass/vinyl ester laminate skins and balsa core, and this material is often used in ship and civil structures. The effect of water exposure via hot (70 °C) and wet (85% relative humidity) environmental conditioning on the (i) water absorption behaviour, (ii) high temperature mechanical properties, and (iii) fire structural properties under combined tensile loading and one-sided radiant heating is experimentally determined.

2. Materials and fire structural testing

2.1. Sandwich composite

The sandwich composite was made with face skins of E-glass/vinyl ester laminate and a core of balsa wood. The skins were fabricated using plain woven fabric (830 g/m^2, Colan Industries) and vinyl ester resin (Derakane 411-350, Nuplex Composites). The glass fabric was stacked in a cross-ply pattern with the warp tows aligned in the same direction. Liquid resin was rolled into the fabric, and the skins were then consolidated using a vacuum bag until the vinyl ester had cured. The two skins were each 1.7 mm thick and had a fibre volume content of about 44%. The core was 6 mm thick Baltek® SB structural end-grain balsa, and the wood grains were aligned in the through-thickness direction of the sandwich composite. The average density of the balsa was 150 kg/m^3, although there is a large amount of variability (standard deviation of ~45 kg/m^3) within a single panel. The initial moisture content of the balsa wood was about 8% by weight. The core was bonded to the face skins using the vinyl ester resin. The sandwich composite was post-cured at 80 °C for two hours.

Table 1 gives the tensile properties of the skin laminate, balsa core and sandwich composite in the dry condition (i.e. before exposure to the hot–wet environment). The glass transition temperature of the dry vinyl ester resin used in the laminate skins was measured to be 120 °C using dynamic mechanical thermal analysis (DMTA).

2.2. Water absorption test

The sandwich composite, glass-vinyl ester laminate used for the skins, and balsa wood for the core were conditioned in an environmental chamber (Sunrise SU600, Angelantoni Industries) at high temperature (70 °C) and relative humidity (85% RH). The samples used to measure the water absorption rate were 55 mm long × 55 mm wide, with a thickness of 1.7 mm for the skin, 6 mm for the core, and 8.4 mm for the sandwich composite. Prior to environmental conditioning, the sides of the samples were sealed with vinyl ester resin. Despite this, water is still expected to be absorbed from the sides of the balsa and sandwich composite specimens due to their relatively large thickness, and this will increase the water uptake rate compared to these materials having perfectly sealed edges. Environmental conditioning of the materials was performed according to specifications of the ASTM D 5229 standard. Water absorption was monitored by weighing the materials using a microbalance (accuracy of 100 mg) following hot–wet conditioning for times up to 26 days (625 h). It is important to note that weight changes to the sandwich composite, laminate skin and balsa core specimens will be caused by chemically-bound water and free-water. However, it is not possible using this test to identify the relative amounts of chemically-bound and free water which cause the weight change to the materials.

Table 1
Average tensile properties of the sandwich composite, skin and core in the dry condition.

Material	Young's modulus (GPa)	Failure stress (MPa)
Sandwich composite[a]	20.5	400
Laminate skin	21.0	437
Balsa wood	1.3	20

[a] Property values calculated assuming skin only.

2.3. High temperature property and fire structural testing

Samples of the laminate skin were removed from the environmental chamber at different conditioning times to measure their tensile properties at room and elevated temperatures. The maximum test temperature was 300 °C, which is close to the decomposition temperature of the vinyl ester used in the skin. Room and elevated temperature tensile tests were performed using rectangular laminate coupons that were 150 mm long, 25 mm wide and 1.7 mm thick. The coupons were loaded in the warp fibre direction at a constant extension rate of 1 mm/min until failure using a 100 kN load capacity MTS machine.

Small-scale simulated fire structural tests were performed on the sandwich composite in both the dry and saturated conditions. The saturated composite samples were exposed to the hot–wet environment for 625 h before fire testing. The test involved axial loading the sandwich composite at a constant tensile stress while simultaneously exposing one surface at a constant thermal flux radiated from a 5000 W electric heater. This test replicates the condition of a tensile-loaded sandwich composite exposed to an intense radiant thermal flux of a fire without direct flame impingement, and the test method is described fully in [26,33]. In the test, a constant tension stress between 10% and 80% of the failure stress at 20 °C was applied to the sandwich composite using a 250 kN MTS machine, as illustrated in Fig. 1. The front skin was insulated from the thermal flux except for a central 100 mm long section of the sample where the heating was consequently localized. The loading machine was thermally protected with insulation and fitted with an exhaust hood to remove fumes and smoke released by the sandwich composite.

The data points in Fig. 2 shows the measured temperatures at the front surface, centre of the core, and back surface of the sandwich composite when exposed to a thermal flux of 35 kW/m^2, reaching a maximum temperature of 520 °C. This heating condition was used to determine the fire structural response of the sandwich composite in the dry and saturated conditions. It is important to note that the measured time–temperature curves for the sandwich composite were virtually identical in the dry and saturated conditions. The thermal code can consider the initial moisture content and thermal predictions confirm minimal influence of the additional water content on the temperature distribution. Hence, the same input values can be used to calculate the temperatures for both the dry and saturated composites (Table 3).

The solid curves in Fig. 2 were calculated using the thermal model for sandwich composites described in Ref. [30]. The thermal model analyses the three important energy transfer processes that occur