Composites: Part A 68 (2015) 323–335

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Development and evaluation of a novel integrated anti-icing/de-icing technology for carbon fibre composite aerostructures using an electro-conductive textile

Brian G. Falzon [a,*], Paul Robinson [b], Sabine Frenz [c,d], Brian Gilbert [e]

[a] School of Mechanical and Aerospace Engineering, Queen's University Belfast, BT9 5AH, UK
[b] Department of Aeronautics, Imperial College London, South Kensington, SW7 2AZ, UK
[c] Imperial College London, UK[1]
[d] Element, Hitchin, Hertfordshire SG4 0TW, UK[2]
[e] Assystem UK Ltd, Preston PR5 6FN, UK

ARTICLE INFO

Article history:
Received 12 April 2014
Accepted 21 October 2014
Available online 27 October 2014

Keywords:
A. Smart materials
B. Electrical properties
B. Thermal properties
B. Damage tolerance

ABSTRACT

The preliminary evaluation is described of a new electro-thermal anti-icing/de-icing device for carbon fibre composite aerostructures. The heating element is an electro-conductive carbon-based textile (ECT) by Gorix. Electrical shorting between the structural carbon fibres and the ECT was mitigated by incorporating an insulating layer formed of glass fibre plies or a polymer film. A laboratory-based anti-icing and de-icing test program demonstrated that the film-insulated devices yielded better performance than the glssass fibre insulated ones. The heating capability after impact damage was maintained as long as the ECT fabric was not breached to the extent of causing electrical shorting. A modified structural scarf repair was shown to restore the heating capacity of a damaged specimen.

1. Introduction

The build-up of ice on aircraft wings can result in severe degradation in lift and loss of aircraft control [1]. Indeed, experimental and computational studies on the effects of ice accretion on aerodynamic surfaces continue to be active areas of research [2–5]. There are two established approaches for mitigating this problem; using an *anti-icing* system to prevent the formation of ice on the wing or other aerodynamic surface during flight, and *de-icing*, which is the removal of ice build-up, usually whilst the aircraft is stationary.

The most common anti-icing system on existing commercial airliners, with a predominantly metallic primary structure, uses hot air from the engine compressor stages which is 'bled' through a network of piping to vulnerable regions and expelled through small holes in the metallic wing skin, which is thereby heated by thermal conduction [6]. The air-bleed reduces the efficiency of the engines and the pipe network adds considerable weight and maintenance requirements. Another established approach, used on smaller commuter aircraft, is to use pneumatic bladders in regions which are most prone to ice build-up, primarily the leading edges. These are inflated to detach ice from critical locations and as such act more as de-icing devices. The dislodged ice debris may impact other parts of the aircraft structure or be ingested by the powerplants, damaging fan blades [7]. Since pneumatic technologies are activated once ice has started to form, some aerodynamic performance is sacrificed prior to de-icing. Due to weight and maintenance implications, anti-icing and de-icing systems are restricted to specific, albeit critical, regions and so ice can still accumulate at other sections of the lifting surface.

De-icing of passenger aircraft is usually performed at airports by technical ground staff spraying the aircraft with a heated Newtonian anti-freeze fluid, usually a dilute solution of monopropylene glycol which is considered non-toxic. Once de-iced, the aircraft has to take-off within an allotted time-frame, otherwise the process needs to be repeated. If the aircraft is likely to be stationary for a longer period, a non-Newtonian glycol solution is applied, which is more viscous, forming a protective layer over the wing which is longer-lasting. Despite the stated non-toxicity of these fluids, concern has been raised by environmental groups on their safety upon entering water systems and some airports have implemented containment systems to prevent such contamination. Another technology which has been installed at a selection of U.S. airports

* Corresponding author. Tel.: +44 (0)28 9097 5640.
E-mail address: b.falzon@qub.ac.uk (B.G. Falzon).
[1] Formerly.
[2] Current address.

http://dx.doi.org/10.1016/j.compositesa.2014.10.023
1359-835X/

involves the use of infrared energy, supplied from the burning of natural gas or propane, through a matrix of outlets distributed over a large canopy under which the aircraft is placed [8].

In recent years a number of alternative systems have been proposed which attempt to improve the power efficiency and operational effectiveness of anti-icing or de-icing. Electro-thermal systems which could be potentially utilised for both anti-icing and de-icing are based on the introduction of a resistive heating element within, or adhered to, the structure. Early examples on metallic aircraft involved the use of a metal foil as the heating element, bonded to the wing's surface. As the aerospace industry moves towards the increased use of carbon–fibre composite material in primary aerostructures, the use of metal foils presents particular challenges in ensuring a durable bond. Hung et al. [9] investigated the use of a brominated conductive graphite fibre-epoxy unidirectional ply between non-conductive glass fibre laminates, Bernthisel and Biller [10] used an expanded graphite foil between insulating polymer sheets and Nino et al. [7] used a layer of glass fibre fabric embedded with continuous metal fibres between glass fibre laminates. Zhao et al. [11] have also explored the use of a multiwalled carbon nanotube sheet, functionalised with silver, as the thermal element bonded onto a Kevlar substructure through a vacuum-assisted resin transfer moulding process. In all cases these systems required the assembly to be effectively adhered to the aircraft surface.

Other investigations have proposed the use of piezoelectric actuators mounted on the inner skin surface to excite the structure at its natural frequencies [12] to break off the ice. Labeas [13] used finite element analysis to simulate the de-icing process arising from the use of an electro-impulsive de-icing system. This technology is based on a system of inductive coils, which act as mechanical actuators, distributed along the inner leading edge surface and attached to the front spar. The impulsive loading, caused by the application of an electric current, induces mechanical vibrations which cause the ice to fracture. While the authors claim that the added weight is comparable to that of existing systems, they acknowledge potential problems with structural fatigue if this system is used regularly. The current generation of passenger aircraft (e.g. Boeing 787 and Airbus A350) have much of their primary structure made of carbon–fibre composite material. This has necessitated the exploration and adoption of alternative anti-icing systems to those which are commonly found on their metallic counterparts. The approach adopted on the leading edge of the Boeing 787 makes use of a molten metal spray, which forms the heating element, deposited onto a glass fibre fabric. Another glass fibre fabric is placed on top of the sprayed metal and this sub-assembly is sandwiched between two carbon fibre composite laminates of the required structural thickness before being vacuum-bagged and autoclave cured [14].

This paper presents a detailed study into the development of an integrated electro-thermal anti-icing/de-icing system particularly suited to carbon–fibre composite aerostructures which could potentially be embedded at the time of manufacture of the wing skins and trailing and leading edge sub-structures. A lightweight carbonised electro-conductive textile, from Gorix, is used as the heating element and two approaches are investigated for isolating this from the rest of the carbon–fibre structure to prevent electrical shorting. The integration of the heater into a carbon–fibre composite panel is described and a preliminary evaluation of the system in both anti-icing and de-icing modes is presented.

The relatively low through-thickness strength and fracture toughness of laminated composite structures makes them particularly susceptible to impact damage [15–18]. Tests were therefore performed to investigate the effect of low velocity impact on the performance of the heater panels and to assess the effectiveness of a modified scarf repair strategy to restore the anti-icing/de-icing capability.

2. Manufacturing trials for the anti-icing/de-icing concept

The approach investigated in this study makes use of a carbonised electro-conductive textile (ECT), manufactured by Gorix, which is highly drapable and easily conforms to complex geometries. It is integrated within the outer surface of the carbon–fibre laminate to provide two primary advantages. The first is that the power requirements, to reach a desired surface temperature, are less than if the electro-conductive heating element is embedded deeper within the carbon–fibre composite laminate since these laminates tend to have low transverse thermal conductivities [9]. This makes possible its use as a de-icing system, which typically requires more power than for anti-icing (the power requirements for this system are investigated later in the paper). The second advantage is the methodology developed for repairing local damage to the ECT and the supporting laminate, which can closely follow the approaches which have been developed for the structural repairs of aerostructural composites.

2.1. Electrical connection to the ECT

For the purposes of this investigation a 10 mm wide copper tape with a conductive acrylic adhesive backing (AT528-50 from Adhesive Tapes International), was used at each end of the ECT heating element. The large contact area, between the ECT and these power connectors, permits a high current flow and power density. To enhance this contact and ensure that the foil is anchored to the ECT, a pattern of holes, shown in Fig. 1a, was punched using a stitching machine. To further enhance conductivity, a thin layer of silver shielding spray (RS247-4251 from RS Components) was applied to the ECT prior to bonding to the copper tape.

2.2. Glass fabric insulation layer

Initial trials showed that, without an insulating layer to separate the ECT and the structural CFRP, electrical shorting occurred and the required heating was not achieved. The use of glass fibre plies for electrical insulation has been successfully tested with other electro-thermal schemes [7,9] and so was investigated here. Specimens (150 mm × 300 mm) were prepared consisting of Hexcel unidirectional CFRP material system (AS4/8552) with a lay-up of $[+45°/-45°/90°/0°]_{4s}$ yielding an overall CFRP laminate thickness of 4 mm. On top of this was placed a layer of ECT (see Fig. 1b) separated from the CFRP by layers of a tight plain weave E-glass fibre fabric (GURIT E-glass RE86P) with an areal weight of 85 g/m^2. In order to avoid stray carbon fibres and particles from the ECT, transferring through the glass weave layers during curing, the ECT was

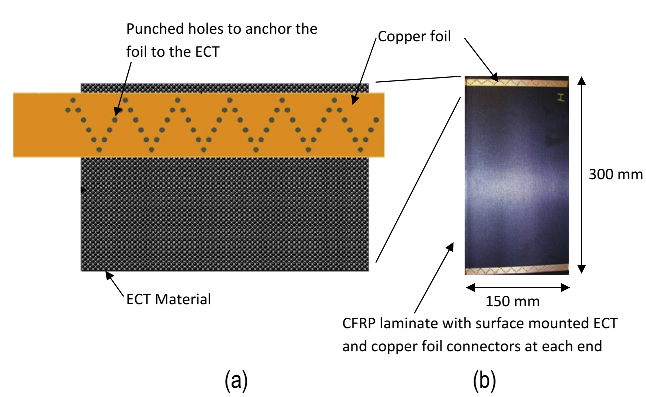

Fig. 1. Copper foil connectors (a) anchoring and (b) heater element. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)