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A mixed adhesion–brittle fracture model and its application to the numerical study of ice shedding mechanisms

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ABSTRACT

The understanding of ice shedding is of prime importance in the assessment of aeronautical ice protection systems. In this paper, the authors previously studied mechanism is extended to include adhesive debonding. It is based on pressure redistribution in the water film formed at the ice/airfoil interface. The numerical modelling of crack propagation is based on recent work on damage mechanics which provides a general framework. As for adhesive debonding an algebraic model is derived from general mechanical equilibrium relations. Numerical experiments are performed to study an adhesive-debonding/brittle-failure mode detachment, the results of which are discussed.

1. Introduction

Icing is a major issue in the aeronautical world. Indeed, this phenomenon has plagued powered flight since the beginning of aviation (at which time it was known as the ice problem) [47,46]. Icing is caused by the supercooled water droplets contained in some types of clouds commonly encountered during flight (cumuliform and stratiform) [1]. When these droplets impact the surface of the aircraft their metastable state is broken and they freeze. This therefore leads to ice build-up, which has several undesirable consequences such as a degradation of aerodynamic performances or blocked air intakes. It is therefore one of the most serious threats which may be encountered in the aeronautical world.

Hence, manufacturers are required to ensure the airworthiness of their aircrafts by complying with strict certifications and regulations. To do so, many ice protection systems have been developed over the years. Today, in the context of more electric aircrafts and the reduction of energy consumption, the electro-thermal ice protection system (ETIPS) is being considered as a promising technology.

This system is composed of electrical heater installed within a multi-layered material and can be used in anti-icing or de-icing configurations [39,43]. The nominal operation of an ETIPS is illustrated in Fig. 1. It first involves what is called the 'parting strip' (heater C). This element is placed near the leading edge and is always active when icing conditions are encountered. This has the effect of keeping the leading edge clean from ice. The other heaters are activated according to a given power cycle. Ice is therefore able to build up in their neighbourhood. When a given heater is activated, the generated heat melts

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Nomenclature

β	interfacial damage variable
ϵ	strain
$\lambda,\ \mu$	Lamé coefficients (Pa)
$\mathcal{H}_\beta$	adhesion history function (J m^{-2})
$\mathcal{H}_d$	brittle fracture history function (J m^{-3})
ϕ	porosity
σ	stress (Pa)
d	damage variable
d_{grain}	grain size (m)
E_{crack}	crack energy (J)
E_{el}	elastic energy (J)
g_c	energy release rate (J m^{-2})
k	effective stiffness of the interfacial bonds (Pa m^{-1})
K_{IC}	fracture toughness (Pa $\sqrt{\text{m}}$)
l	regularization length
L_b	critical brittle failure length (m)
L_f	length of melted region between ice and protected surface (m)
L_t	total contact length between ice and protected surface (m)
P_c	contact point between melted region and airflow
$p_{exterior}$	exterior pressure distribution (Pa)
$p_{redistributed}$	redistributed pressure (Pa)
u	displacement (m)
w	adhesion energy (J m^{-2})

the ice at the interface. The ice is then less able to stay attached to the surface and is eventually shed by the effect of the aerodynamic forces.

The understanding of ice shedding is of prime importance in the assessment of the performance of an ETIPS. It is essential to understand by which mechanisms the aerodynamic forces are able to detach the ice. However, very few studies exist and ice shedding is to this day still not well understood. Experimental studies dealing with the precise mechanisms of ice shedding are almost inexistent and present extremely scattered results [5,41].

On the numerical side, Scavuzzo et al. performed a finite element analysis of the stress distribution due to aerodynamic forces in an accreted ice block [40]. More recently, Zhang et al. have used a crack propagation and re-meshing technique to study ice break up [2]. However these studies did not take into account the effect of an ice protection system.

From a practical point of view, ice shedding is taken into account in state of the art icing codes by using a highly empirical criterion. The criterion works by comparing the length of the liquid water film formed at the interface with the whole contact length. It states that, if the ratio of these two lengths exceeds a user defined value (typically 80% of the whole contact length), then the ice block detaches [39]. However, such an empirical criterion is unsatisfactory. Therefore, to obtain more physical ice shedding models, a better understanding of the detachment process is needed.

In this paper, the authors build upon their previous study [24] by incorporating new possible debonding mechanisms. First, the proposed detachment mechanisms are presented. Then, the modelling and numerical techniques used in this study are introduced. This will be followed by a parameter identification after which numerical experiments are performed. Finally the results are discussed.

As shall be stressed out later, it is extremely difficult to characterize the mechanical properties of atmospheric ice. Hence, it should be noted that the goal here is not to provide highly accurate predictions. It is rather to propose a general methodology which can be used to explore and explain different ice shedding mechanisms in a qualitative way, opening the door to their experimental investigation. The presented methodology is moreover general enough to be applied to the study of other problems. In addition, this approach has the advantage of locally predicting the initiation of detachment or fracture.

With this approach, qualitative progress is sought on the comprehension of the physical mechanisms at play, in particular concerning the interplay between adhesive detachment and brittle failure. Indeed, this aspect is of great importance to the design of electro-thermal ice protection systems (heating cycles, choice of materials, etc.).

2. Proposed mechanism

Let us consider the following situation (illustrated in Fig. 2). In the nominal functioning mode, ice has built up just aft the parting strip. In due time, the corresponding heater will be activated. This will lead to the creation of a liquid water film, extending over a distance L_f, between the surface and the ice. Due to hydrostatic equilibrium, the pressure exerted by the