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Durability of CFRP laminates under thermomechanical loading: A micro–meso damage model

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Abstract

A pragmatic approach is here proposed for the description of the degradation of laminated composites under cyclic loading, including the effect of oxidation. It is based on an hybrid micro- and mesomodeling of the degradation which includes and generalizes classical micromechanical approaches for static loading. The effects of cyclic loading and of the environment are then taken into account through the consecutive decrease in critical quantities.

Keywords: Micromechanics; Fatigue; Microcracking; Oxidation

1. Introduction

Due to the importance of their specific properties, carbon/epoxy laminated composites have acquired a major place in aeronautics and space applications. This interest has given rise to numerous research works on their damage behavior on all scales (especially in micromechanics: [1–3]; and mesomechanics: [4,5]). Today, as a result, we have a good understanding of their behavior under classical loading, which enables us to use them in the design of low-temperature, non-vital applications, such as tailcones and some parts of the fuselage of subsonic airplanes.

A new challenge proposed by the aeronautics community is now to extend the use of these materials to more critical applications, one of these being a future supersonic civil airplane to be developed in the framework of the French "Aeronautical Supersonic Program" supported by the Ministry of Research and the Ministry of Equipment, Transport and Housing. In this particular application, the material will be subjected to intensive thermal cycles (four-hour takeoff/landing cycles). In addition to classical fatigue damage, because of the relatively high temperature (approximately 130 °C at Mach 2.0) and the presence of oxygen, degradation due to the progressive oxidation of the material will also occur. In fact, the degradation process is a much more complex combination of static degradation, fatigue damage and oxidation-induced degradations, resulting in the rapid development of elaborate patterns of degradation, especially microcracking [6–8].

Due to the long anticipated lifetime of the application (20,000 flights, i.e., 80,000 h), its design requires the development of appropriate accelerated tests. In order to design these accelerated experimental conditions, one must be able to rely on a model with sound physical content, which is sufficiently accurate for extrapolation. The aim of this paper is to propose such an approach for predicting the degradation of aeronautics structures under these conditions.

The paper is divided into four parts.

In the first part, the micromechanical approach used to describe degradation under static loading (especially transverse microcracking) is reviewed. This model, which was developed in previous works [9,10], is a general micromechanical approach which can be used in association with a suitable computational strategy for structural calculations. In fact, it is an hybrid model. In part, it is discrete in that cracks are described through the a priori introduction of cracking surfaces. However, continuum damage

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mechanics is used for progressive degradation mechanisms, such as fiber/matrix debonding. A simplified microcracking law developed for this model is presented at this point and will be used for identification purposes in parts two and three.

In the second part, the modeling of fatigue damage is presented. In our approach, even under cyclic loading, microcracking is still assumed to be governed by the static evolution law [10,11]. The only consequence of cycling is a reduction of critical microcracking tenacities. Thus, microcracks appear simply due to the weakening of the intercrack materials. Whereas classical micromechanical approaches introduce specific laws for fatigue microcracking, this approach completely unifies the descriptions of microcracking under static loading and under fatigue loading, since the important concept of critical energy release rate is preserved. Here, the loss of critical tenacity due to fatigue is quantified thanks to a new internal variable. Some examples of the typical range of this variable for classical experimental results taken from the literature [12] are presented and an associated evolution law is proposed.

The third part describes the introduction of the environment, especially an oxidizing atmosphere at high temperature, into the model. Here again, critical tenacities and microcracking are in the foreground. These are defined as functions of the temperature and of the partial oxygen pressure. Several simplifications are proposed and an estimation of this oxidation-induced reduction of tenacities for several environmental conditions is given.

Finally, the basic modeling aspects described in the first three parts using a simplified approach are introduced into the complete computational micromechanical approach. The last part presents first calculations based on experimental observations [8,13]. These lead to a computational model based entirely on quantities which have a strong material interpretation. We hope that such a micromechanics-based model will make predictive extrapolations accessible in the near future.

2. A short review of micromodeling under static loading

2.1. The damage mechanisms on the microscale

We assume that any complex state of degradation of a laminated composite results from the accumulation followed by the localization of four elementary mechanisms which are clearly identified on the microscale (Fig. 1).

The first two mechanisms ("*transverse microcracking*" and induced "*local delamination*") are usual and have been studied by the micromechanics community in numerous works, mostly in the framework of finite fracture mechanics as these mechanisms are "discrete" on the ply's level (see [14,15] for reviews).

The last two mechanisms ("*diffuse damage*" associated with fiber-matrix debonding, and "*diffuse delamination*" associated with microvoids within the interlaminar interface) are usually not introduced on the microscale, but

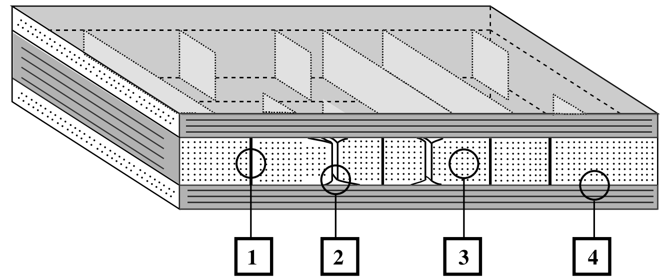

Fig. 1. The mechanisms of degradation on the microscale: $\boxed{1}$ transverse microcracking; $\boxed{2}$ local delamination; $\boxed{3}$ diffuse damage; $\boxed{4}$ diffuse delamination.

have been introduced on coarser scales for a long time, e.g., in the damage mesomodel for laminates [16,17].

2.2. The computational damage micromodel for laminates

Although the micromechanics of laminates has been studied extensively, few of the available models enable the designer to carry out actual calculations on engineering structures. The formalism of most of the proposed approaches applies only in very specific cases.

Recently, a computational micromodel was proposed for the description of microcracking, local delamination, (visco)plasticity and diffuse damage in engineering structures [9,18]. This is, in fact, a hybrid approach (Fig. 2).

This model is, in part (transverse cracking and local delamination), discrete. In a general way, minimum cracking surfaces can appear gradually for these mechanisms during the computation. An easier method is to introduce a priori minimum cracking surfaces within the discretization of the structure. The failure criterion for each elementary cracking area is defined through well-known micromechanical considerations (the distinction between the initiation and propagation of transverse microcracking and the induced thickness effect: [19,20]). One can say that at least for that part the model belongs in finite fracture mechanics.

For the rest, diffuse damage and (visco)plasticity are described through continuum mechanics models. Diffuse damage is quantified by two damage indicators, $\tilde{d}'$ in the transverse direction and $\tilde{d}$ in the shear direction, which are assumed to be homogeneous within each elementary

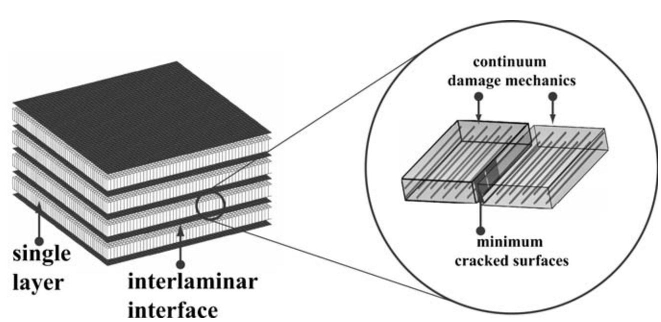

Fig. 2. The computational damage micromodel: minimum cracking surfaces.