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Fatigue damage and stiffness evolution in composite laminates: a damage-based framework

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Abstract

A damage-based design procedure has been developed by the authors to predict the damage evolution and the stiffness degradation in polymeric composite laminates under fatigue loading. For a safe and reliable design against fatigue degradation and failure, the initiation of the main damage mechanisms (off-axis cracks, delamination and fiber failure) as well as their evolution are considered and suitable models are proposed for the quantitative assessment of the lifetime associated to each mechanism. In parallel, the stiffness degradation deriving from the damage evolution over the fatigue life is properly described. After the illustration of the overall damage-based strategy, the paper discusses in details the analysis and modelling of the off-axis crack initiation and propagation. The initiation of cracks in the off axis plies has been proved to be the consequence of a damage process occurring at the microscopic scale since the early stages of fatigue. On this basis, crack initiation prediction is based on the use of local stress parameters: Local Hydrostatic Stress, LHS, and Local Maximum Principal Stress, LMPS, depending on the local degree of multiaxiality of the stress state and accounting for the statistical distribution of the local laminate strength. The propagation phase is then quantified by using a conventional fracture mechanics approach. The model has been implemented in a Matlab procedure for the quantitative evaluation of the crack density in each ply of a laminate during its entire fatigue life. The knowledge of the crack density trend allows the description of the laminate stiffness evolution taking advantage of another model recently developed by the authors, valid for a generic laminate configuration and accounting for the interaction between cracks in the neighbouring plies.

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Keywords: Composites; Fatigue; Damage mechanisms; Stiffness degradation; Damage modelling

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1. Introduction

Composite materials are excellent candidates for the development of reliable lightweight components and structures complying, for instance, with the needs of decreasing fuel consumptions in the transportations field or increasing the specific energy production in the wind energy field.

Most of structural components manufactured with composite materials are subjected during their in-service life to cyclic loadings, which might lead to a progressive damage, a consequent loss of stiffness and residual strength and, eventually, to the final failure. The "design against fatigue" is therefore fundamental to improve the reliability of composite structural parts.

To meet the demand of fatigue design tools for composite structures, the Composite Group at DTG-University of Padova is working since several years to the development of a design framework suitable to predict the initiation of damage, its evolution and the final failure of composites under cyclic loadings [1-11].

As a starting point of the discussion, it is important to clarify the concept of "design against fatigue", which can be meant in different ways depending on the requirements of the part under design:

i) design against crack initiation (no damage);
ii) design against stiffness degradation (damage tolerant design);
iii) design against final failure.

In applications like fuel and pressure vessels, fuel rails or other, the onset of damage has to be avoided to satisfy the safety requirements. In this case, the capability to predict the life spent for the initiation of the first crack is essential. In other cases like automotive composite frames, turbine blades, bicycle cranks or composite rims, the global stiffness can be the design driver. Due to the several fatigue damage mechanisms, structural composite components can lose up to 30-40% of their initial stiffness (depending on lay-up and load conditions) much before the final failure. Therefore, for a more reliable and cost-effective design, it is important in these cases to estimate the stiffness degradation under the specific loading conditions [6].

When only the load bearing capability of the part is of interest, the final failure (separation into two or more pieces) is the design target.

In the authors' opinion, the only way to deal with such a complicated phenomenon and provide suitable and reliable design tools for the three targets above is to develop models and criteria based on the actual damage mechanisms occurring at the different scales.

As shown in several works in the literature [2, 4, 7, 10, 12-16] the first observable damage event is the initiation and subsequent propagation of off-axis cracks. The crack density increases until reaching a sort of plateau that corresponds to the fading of the crack multiplication and the saturation of the crack density. In this phase, it is possible to observe a significant degradation of the laminate stiffness. The saturation is slightly preceded or followed by the initiation of delaminations triggered by the presence of the off-axis cracks. Delaminations propagate at the plies' interface causing a further stiffness degradation. These mechanisms are not directly responsible for the final failure, however they indeed promote the failure of the fibres until a critical condition is reached, in which the load bearing plies are not able anymore to carry the applied load. This corresponds to the final failure of the laminate.

According to this scenario, a reliable model for the prediction of the fatigue damage initiation and evolution should be able to describe (Figure 1):

- The cycles spent for the crack initiation;
- The crack density evolution (multiple crack initiation and propagation) until the saturation;
- The cycles spent for the delamination initiation and propagation;
- The cycles spent for the final failure, driven by the fibre breaks.