MODELLING INITIATION AND EVOLUTION OF FATIGUE DAMAGE IN COMPOSITE LAMINATES

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Abstract
In the present work an overview is presented on a model which is being developed by the authors for the prediction of fatigue damage and failure of composite laminates. In particular the strategy for predicting the initiation and propagation of off-axis cracks and the crack density evolution is described. Then some experimental evidences and modelling efforts are presented for the problem of the initiation and propagation of delaminations.

1. Introduction

Most of structural components manufactured with composite materials are subjected to cyclic loads during the in-service life, which might lead to progressive damaging and, in turn, to the loss of stiffness, residual strength and, eventually, to final failure.
Thus, the "design against fatigue" is essential to improve the reliability of composite structural parts. The design against fatigue can aim at:
i) avoiding crack initiation (no damage);
ii) avoiding a certain stiffness degradation;
iii) avoiding final failure.
If the design aim is avoiding the onset of any kind of damage, being able to predict the cycles spent for the initiation of the first crack is essential.
In other circumstances, a damage tolerant approach can be adopted. In these cases avoiding fatigue failure is of course the most trivial goal in the design of a component. However, because of the damage evolution characterising the fatigue life of composite laminates, they can lose a significant part of their stiffness (up to 30-40%, depending on the lay-up) much before the final failure. As stiffness is often one of the most important parameters in the design process, being able to predict its degradation is essential for a safer and cheaper design.
As it will be deeply discussed later, the development of damage in composite laminates is characterised by several mechanisms, from the damage initiation at the microscopic scale to the onset and propagation of macro-cracks and delaminations leading to final failure. These mechanisms are also dependent on the materials adopted, the lay-up and the loading type and multiaxial conditions [1].
The only way to deal with such a complicated problem is to develop models based on the damage mechanisms actually occurring at the several length scales [1] and link them in a multiscale and multi-mechanisms design procedure.
The authors are working since several years in the characterisation and modelling of the fatigue damage evolution of composite laminates.
In this work the strategies developed for predicting the initiation and evolution of the damage in multidirectional laminates are briefly presented.

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2. Modelling off-axis cracking

If design target is avoiding the final failure, the entire damage process must be modelled, with the aim to predict the cycles spent for the first crack initiation ($N_{i,c}$), the cycles for crack multiplication and propagation ($N_{p,c}$), the life to the initiation of delaminations ($N_{i,d}$), the cycles spent for the propagation of delaminations ($N_{p,d}$) and eventually the final failure (N_f) (see Figure 1).
However, from the experimental observations reported in the literature [2,3] it is clear that a composite part under fatigue loading can lose a significant amount of stiffness, and therefore become unsuitable for in-service application, much before its final failure. For this reason, and considering the importance of stiffness as a design parameters for composite structures, it is important to develop a model to predict also the degradation of elastic properties throughout fatigue life. Such a model would allow a more reliable and also optimised design to be made.
A damage-based design procedure has been recently developed by the authors to predict damage evolution and the stiffness degradation in composite laminates. It will be briefly described in the following.
As already proved, the stiffness degradation is mainly due to the initiation and propagation of multiple off-axis cracks. Therefore a criterion to predict crack initiation, capable of accounting for multiaxial stress states, must be defined. Also in this case, a damage-based approach is necessary, mainly considering the multiscale nature of composite materials. In fact, the initiation of a macro-crack is the consequence of a damage process occurring at the microscopic scale (the length scale of the inter-fibre distance) since the early stages of fatigue. This was proved by the present authors [4,5], who showed that the initiation of an off-axis crack was the result of the initiation, accumulation and coalescence of multiple micro-cracks in the matrix, inclined to the fibres, at least in the presence of shear stress, as shown in Figures 2a) and b).
On the basis of the damage modes observed at the microscopic scale, Carraro and Quaresimin [6] proposed a criterion for crack initiation based on the use of local stress parameters (Local Hydrostatic Stress, LHS, and Local Maximum Principal Stress, LMPS) as equivalent stresses for the representation of the S-N curves, which resulted in good agreement with a large bulk of experimental data. This criterion, coupled with the classical lamination theory, is useful to predict the initiation of the first cracks is the off-axis plies of a laminate. Predicting the crack density evolution, which can be then correlated to the stiffness degradation, requires to include a more refined stress analysis to evaluate the stress fields in the plies considering the stress re-distribution due to the presence of already initiated cracks. Such a model was also developed by the authors [7]. This analytical model, a part from computing the stress re-distributions, allows one to calculate with a very good accuracy the laminate stiffness on the basis of the crack density on its plies.
Based on the crack initiation criterion, combined with fundamental statistical considerations, on the stress-redistribution and stiffness model, and using Paris-like curves to describe crack propagation, the authors developed a procedure for predicting the crack density evolution and then the stiffness degradation under fatigue loading [8]. The procedure is a simulation of fatigue life, implementing the above mentioned analytical tools within a code. A schematic flow-chart is shown in Figure 3.

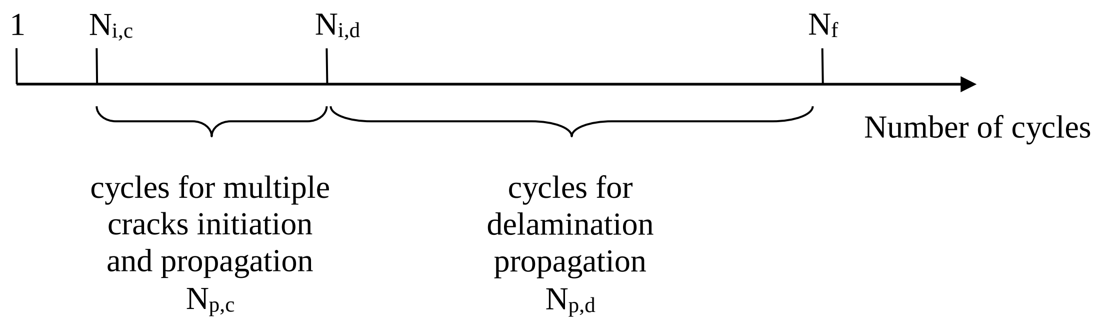

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Figure 1. Typical sequence of damage mechanisms in multidirectional laminates under fatigue

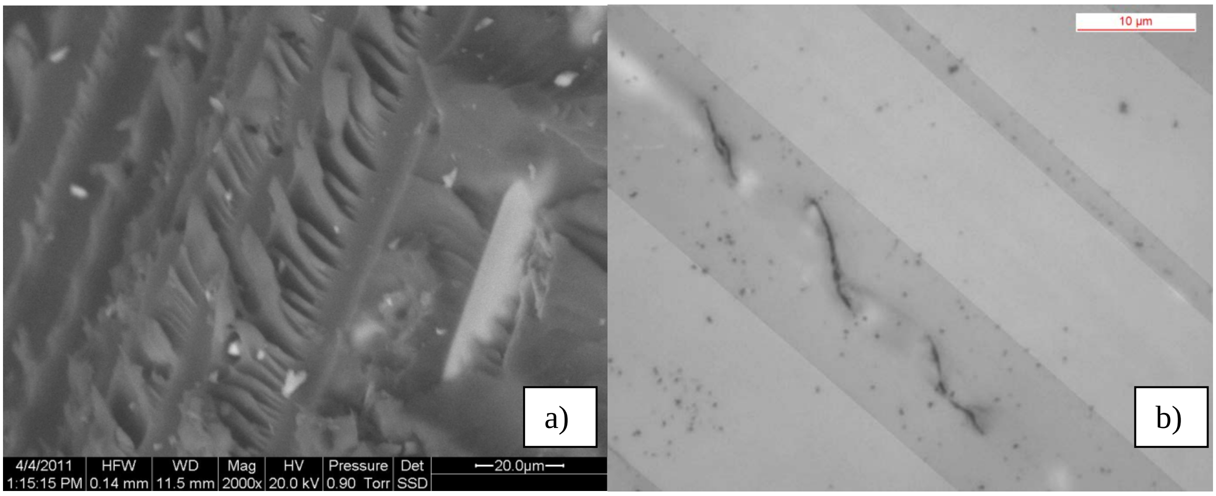

Figure 2. Damage mechanisms at the microscopic scale: a) SEM image of a fracture surface and b) micrograph on an off-axis ply under fatigue loading

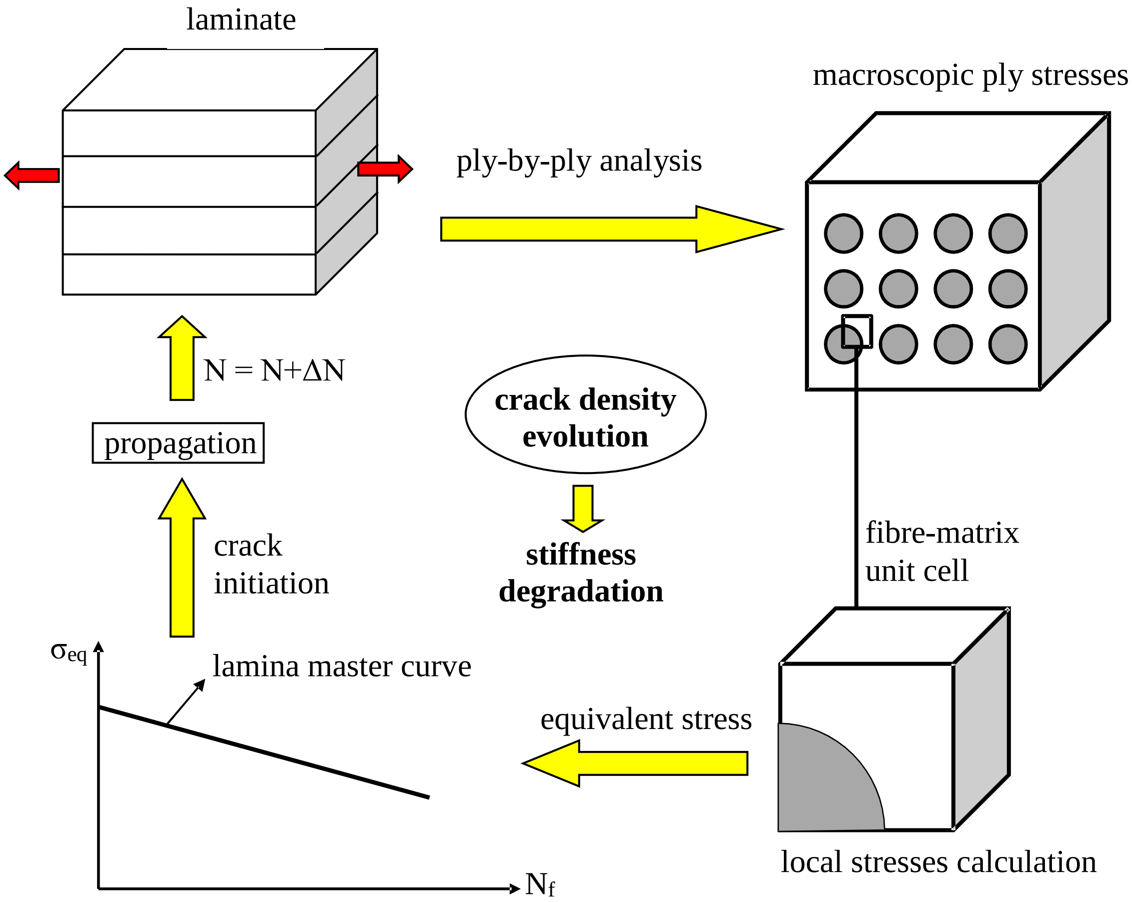

Figure 3. Schematic of the procedure for predicting damage evolution and stiffness degradation in multidirectional laminates

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3. Characterisation and modelling of the delamination propagation

With the aim to extend the damage evolution model to describe the initiation and propagation of delaminations, initially an experimental campaign was conducted. Fatigue tests were carried out on glass/epoxy cross-ply laminates, focusing the attention on the initiation of multiple transverse cracks and also on the initiation and propagation of delaminations from the nucleated transverse cracks. It was observed that the crack density saturation and the initiation of delaminations occurred at a very small percentage of the total fatigue life (1-2%), so that the cycles spent for these phenomena can be even neglected if the final failure is the target of the analysis.
The delamination length was measured during the fatigue tests (figure 4a), the relevant values of the mode I and II Energy Release Rate (ERR) were computed with Finite Element analyses and the VCCT technique, and eventually related to the delamination growth rate to obtain Paris-like curves (figure 4b). This tool allows the delamination length to be predicted as a function of the number of cycles, and the related stiffness loss to be estimated, by means of analytical models as for instance a shear lag model (figure 5), in which both the effects of transverse cracks and delaminations is included.

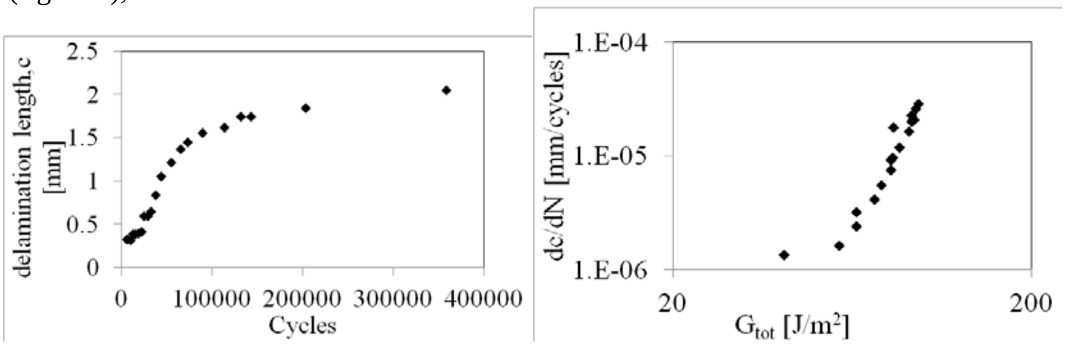

Figure 4. a) Example of delamination length evolution and b) relevant Paris-like curve

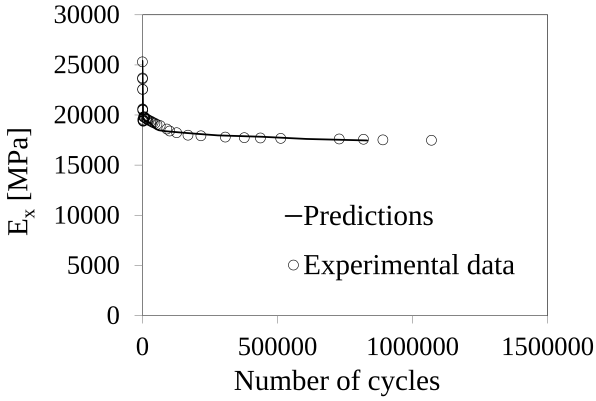

Figure 5. Prediction of the laminate Young modulus with a shear lag model including the effect of delaminations

4. Conclusions

In composite laminates under fatigue loadings, the damage initiates and evolves since the early stages of the life, leading to the degradation of the stiffness and then to the final failure. To predict this scenario, which is essential for a better and safer design process, a damage-based approach must be adopted. The different damage mechanisms characterizing the fatigue life of a laminate and their effect on the mechanical properties must be taken into account. To this aim, the present authors have

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developed a model to predict the initiation and evolution of off-axis cracks and delaminations and the consequent stiffness degradation.

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