DAMAGE INITIATION AND EVOLUTION IN COMPOSITE LAMINATES UNDER CYCLIC LOADING: A DAMAGE-BASED MODELLING FRAMEWORK
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ABSTRACT

The paper illustrates, briefly, the fatigue design strategy, based on the physics of the damage evolution, under development by the Composite Group at DTG-University of Padova. After a brief introduction, examples of damage mechanisms at the microscopic scale are presented and the procedures for the quantitative description of these mechanisms are illustrated.

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 transportation 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 for instance fuel and pressure vessels or fuel rails, 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 reliable design tools to serve for the three targets mentioned 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 delamination, 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 to carry the applied load anymore. This corresponds to the final failure of the laminate.

According to this damage scenario, any model for the prediction of the fatigue damage initiation and evolution should be able to describe (Figure 1):
- the cycles spent for the first 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, strongly influenced by the previous damage evolution.

In the next sections, the modelling strategy recently proposed by the authors is presented, concerning the crack initiation, propagation and multiplication. Then the ongoing activity the authors are carrying out to assess the problem of delaminations is presented.

**2. CRITERIA FOR CRACK INITIATION AND PROPAGATION**

**2.1 Criterion for crack initiation**

A model for predicting the cycles spent for crack initiation in UD composites was presented by Carraro and Quaresimin [5]. It is important to remember that in the plies of a composite laminate the stress state is basically always multiaxial, it being due to external loads in multiple directions or to the material anisotropy. The criterion proposed by the authors takes into account the multiaxial stress state on the basis of experimental observations of the damage mechanisms occurring at the microscopic scale. It was observed that, if the shear stress in a ply is high enough with respect to the transverse stress, as for instance in a 45° ply, the initiation of an off-axis crack is due to the onset and coalescence of micro-cracks as shown in Figure 2 [5]. It was also proved that the orientation of these micro-cracks, named by the authors \textit{local nucleation plane}, is normal to the Local Maximum Principal Stress (LMPS) in the matrix [5]. Accordingly, Carraro and Quaresimin proposed to use the LMPS as the driving force parameter to predict the crack initiation under these conditions. If the shear stress is much lower than the transverse stress, the micro-scale damage is instead driven by the Local Hydrostatic Stress (LHS), as shown by Asp et al. under static loading. Therefore, the LHS in proposed in this case to predict the crack initiation when the shear to transverse stress ratio ($\lambda_{12}$) is lower than a certain threshold. The LHS and LMPS are local parameters that can be calculated by means of Finite Element (FE) analyses of a fibre-matrix unit cell with proper boundary conditions as explained in Ref. [5].

![Schematic of the modelling strategy for the life assessment of composite laminates](image-url)
In Ref. [5] the criterion was validated against several initiation data from the literature, showing a very good agreement. Examples are shown in Figure 3, where crack initiation results in glass/epoxy tubes are presented in terms of the transverse stress (3a), the LHS (3b) and LMPS (3c) for different biaxiality ratios. It can be seen that all the data are collapsed into two scatter bands, to be used for the crack initiation prediction when the biaxiality ratio is higher or smaller than a threshold equal to 0.5, for the material under analysis.

Figure 3: First crack initiation results for glass/epoxy tubes [2]: maximum a) cyclic transverse stress, b) LHS and c) LMPS against the number of cycles for first crack initiation
2.2 Criterion for crack propagation

When an off-axis crack initiates, it starts propagating along the fibre direction. It was shown that the crack growth rate can be predicted from the Energy Release Rate (ERR) through a Paris-like law [2, 4, 7, 10]. It is important to mention that the ERR for tunnelling cracks does not depend on the crack length, so that their propagation is referred to as a steady state phenomenon. Conversely, the ERR depends on the crack density. In fact, the higher is the crack density, the lower is the ERR because of a shielding effect [4].

The steady state value of the ERR can be easily calculated, as a function of the crack density, by means of analytical models (see Ref. [6] and the references quoted therein) or FE analyses.

In general, the off-axis crack propagation occurs in mixed I+II mode conditions, so that the Paris-like law should be expressed in terms of an “equivalent” ERR, $G_{eq}$, that accounts for the mode mixity $MM = G_{II}/G_{tot}$. It is known that the propagation of an interface crack in mixed mode conditions, but close to pure mode I, is driven only by the mode I component, so that $G_{eq} = G_I$ for $MM$ lower than a certain value (around 0.5) (see Refs.[2, 18] and the references quoted therein).

When the loading condition is characterised by a dominant mode II component, the micro-scale mechanism of crack propagation changes, as shown in Refs. [3, 18]. The authors are currently working to the definition of a damage-based equivalent ERR to be used in these conditions. However, for the time being Carraro et al. [11] proposed to use $G_{eq} = G_{tot}$ for $MM$ higher than 0.5, but lower than 1.

3. A MODEL FOR THE CRACK DENSITY EVOLUTION

The crack initiation criterion described in the previous section, combined with a simple stress analysis tool such as the classical laminate theory (CLT), can be used for predicting the first crack initiation within a ply in a laminate, once a certain probability of survival is given. The prediction of the crack density evolution is instead much more complicated and it was approached by the authors according to the following basic ideas [11]:

- The initiation of multiple cracks can be treated using S-N curves for crack initiation in terms of the local parameter LHS or LMPS. At this point, the statistical distribution of the fatigue strength to crack initiation has to be considered, this being the only explanation for having crack initiations at different number of cycles;
- The CLT is not suitable for the stress analysis of a laminate in the presence of cracks. To overcome this limitation, Carraro and Quaresimin developed a suitable stress re-distribution model [6] based on an optimised shear lag analysis;
- The off-axis crack growth rate can be predicted with a Paris-like curve as a function of the energy release rate, that can be calculated on the basis of the actual crack density.

Then, the model for the crack density prediction consists in the simulation of the fatigue life by progressively increasing the number of cycles by steps $\Delta N$.

For a given step of fatigue cycles $\Delta N$, and for every off-axis layer, the following steps are taken:

1) Calculation of the stresses in each layer, considering the stress re-distribution due to the presence of cracks.

2) Calculation of local stresses by means of a fibre matrix unit cell subjected to periodic boundary conditions (see the stress concentration factors defined in Ref. [5]).

3) Calculation of the LHS and LMPS.

4) According to the multiaxial condition, calculation of the total density of nucleated cracks, by using the LHS of LMPS master curves and the associated statistical distribution of the fatigue strength for the material considered.
5) Analysis of the crack propagation phase to compute the length of all the nucleated cracks.

6) Increasing the number of cycles of a quantity \( \Delta N \) and repeat steps 1)-6) until the required number of cycles or crack density saturation is reached.

An example of the validation of the crack density prediction model is shown in Figure 4a, for a glass/epoxy laminate tested at different load levels [11].

Once the crack density is known in all the plies of a laminate, it can be used as an input for the stiffness degradation model developed by Carraro and Quaresimin [6]. This model was developed for generic laminates with cracks in one or more plies and it accounts for the interaction between cracks in different layers. An example of the final result is given in Figure 4b, where, for the same laminate, the predicted stiffness degradation is compared to the experimental measurements, showing a very good agreement.

4. ANALYSIS OF THE DELAMINATION ONSET AND PROPAGATION

As mentioned in the introduction, the next mechanism occurring during the fatigue life is represented by delamination, whose propagation causes a further, even if typically lower, stiffness degradation and plays an important role in the fibres failure process.

With the aim of characterising the delamination initiation and propagation, the authors have recently conducted a dedicated experimental investigation. Fatigue tests were conducted 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 induced by the transverse cracks themselves. The Young modulus was measured throughout the fatigue tests, obtaining normalized trends as that shown in Figure 5. The crack density and the delamination ratio, meant as the ratio between the delaminated area and the total area of the gage length, were measured from images taken in situ. They are plotted in Figure 5 as well. 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. It can also be observed that most of the axial stiffness is lost in the very early stages of the test, meaning that it is due to the crack density evolution. The propagation of delaminations instead provides a lower contribution in the stiffness loss. However it is an important phenomenon to be treated because it triggers the failure of the load bearing fibres in a larger and larger region of the laminate.

The delamination length was measured during the fatigue tests (figure 6a), 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. It was possible to define a Paris-like
curves relating the growth rate to the mode II energy release rate (the mode I contribution is very limited or absent, at least under tensile loadings) (figure 11b).

This approach allows the delamination length to be predicted as a function of the number of cycles. The authors are currently working to include also this mechanism into the predictive framework described in the previous sections.

![Fig. 5: a) Normalized Young modulus, crack density and delamination ratio for a glass/epoxy [0/902]s laminate tested with a global laminate stress of 120 MPa; b) zoom of the first 10000 cycles](image)

**Figure 6:** a) Example of delamination length evolution and b) relevant Paris-like curve

**REFERENCES**


