# A TOOL FOR THE SIMULATION OF FATIGUE DAMAGE EVOLUTION IN MULTIDIRECTIONAL LAMINATES

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**Abstract**
*In the present work, a software tool is presented to predict the crack density evolution in the off-axis layers of multidirectional laminates under fatigue loading. The software implements an analytical procedure developed by the authors and presented in a companion paper. It treats separately the multiple crack initiation and propagation phases by means of S-N and Paris-like curves of the UD material. The predicted crack density evolution is used as input for a model developed by the authors for the estimation of the stiffness drop due to the presence of off-axis cracks. Here the input data and the output results of the software will be presented. Eventually the procedure is validated against experimental results for crack density evolution in multidirectional laminates.*

## 1. Introduction

The fatigue life of multidirectional laminates is characterised by a progressive stiffness degradation, which can make a laminate unsuitable for its service function much before its final failure. This is caused by the initiation and propagation of multiple matrix cracks in the off-axis layers [1-3]. Accordingly, it is of fundamental importance to be able to predict the crack density evolution during fatigue life, to be used as input for the estimation of the elastic properties degradation. Several models can be found in the literature that correlate the crack density to the laminate stiffness [4-7]. A model was also developed by the authors which is able to compute stress and displacement fields, as well as the global elastic properties of a laminate with cracks in multiple layers, accounting for the interaction between cracks in different layers [8,9]. This model requires as input the crack density in each layer of the laminate.

Thus, a procedure for the prediction of the crack density evolution under fatigue loading has been proposed by the present authors in a companion paper [10]. As highlighted in Ref. [10], for a proper estimation of the stiffness degradation, the so called *weighted* crack density has to be predicted. It is equal to the sum of the initiated cracks, each being weighted by its length, divided by the observation length. Therefore, the prediction of the weighted crack density evolution must include the crack initiation and propagation phases.

The initiation phase is treated by means of the S-N curve of a single lamina expressed in terms of an equivalent stress $\sigma_{eq}$, capable of dealing with multiaxial stress states. As shown in Ref. [11] the equivalent stress can be the Local Hydrostatic Stress (LHS) or the Local Maximum Principal Stress (LMPS), which are local quantities to be calculated with a multiscale strategy. As discussed in [11], they can be linked to the in-plane ply stresses $\sigma_1$, $\sigma_2$

and $\sigma_6$ by means of local stress concentration factors. The procedure presented in [10] accounts also for the statistical distribution of fatigue life and of the stress redistributions after cracking, by means of the shear lag model proposed by the authors [8,9].
The length of the initiated cracks is then predicted by means of the material Paris-like law relating the Crack Growth Rate (CGR) to the Energy Release Rate (ERR or G). The Paris-like equation is expressed in the form $CGR = D \cdot G_{eq}^n$, where $G_{eq}$ is an equivalent ERR suitable to deal with mixed mode I + II loading, as discussed in Ref. [10].
In the present work, a software tool with graphical interface is developed in the Matlab® environment for the prediction of the *weighted* crack density evolution in the off-axis layers of a generic symmetric multidirectional laminate under fatigue loading. The stiffness degradation model proposed by the authors is also implemented to provide the prediction of the stiffness degradation of the laminate, thus representing an important tool for the design of structural components against fatigue damage. The developed software tool is presented in terms of methodology, input variables and results. The reader is referred to [10] for a more comprehensive explanation of the model.

## 2. Program inputs

Based on the model presented in [10], a Matlab® program was developed that allows the prediction of the *weighted* crack density evolution and stiffness degradation of a symmetric laminate with any number of plies during fatigue life. A graphical user interface was made in order to make the program more user-friendly, and the input data are given through a given Excel® file.
As inputs, the following material data are required:

- Elastic properties of the material (longitudinal and transverse Young's moduli, in-plane and out-of-plane shear moduli, in-plane Poisson's ratio);
- Slope, *a*, of the material S-N curve in the form $\sigma_{eq}=K \cdot N^a$ in terms of LMPS and in terms of LHS, and the value of the LHS/LMPS ratio at which the equivalent stress shifts from one parameter to the other;
- The coefficients of the Paris-like curve of the material in the form $CGR=D \cdot G_{eq}^n$;
- The mechanical and thermal stress concentration factors (see Ref. [11]);
- The laminate geometry (off-axis angles, thicknesses of the layers and laminate width);
- The scale and shape parameters of the Weibull distribution for the K parameter of the S-N master curve, for each layer.

The steps of number of cycles at which the calculations has to be performed is needed too, as well as the value of the maximum global stress applied in the loading direction.
The elastic properties can be obtained by static tests, the S-N curves by fatigue tests on a UD lamina at two different $\sigma_6/\sigma_2$ ratios (high for LMPS, low for LHS, [11]). The Paris-like curve parameters can be determined by means of crack propagation tests in constrained UD laminae (see Refs. [1,12]), and the stress concentration factors by FE analyses on fibre-matrix unit cells as shown in [11]. The ERR components are computed, as a function of the crack density, by the program by means of a shear lag analysis. However, it is also possible to provide a function describing the ERR against crack density trends, obtained with FE analyses for instance, as an input.

## 3. Program Outputs

As described in Ref. [10], the procedure carries out a simulation of fatigue damage evolution of a laminate under a given applied global stress. For each value of the number of cycles given in the input file the code predicts the initiation of new edge cracks by means of the S-N

curve, and related Weibull parameters, for the UD plies. Then it computes the ERR components and the crack length by means of the Paris-like law given as input.
The program generates the following outputs:

- The total crack density (total number of cracks per unit length) and the *weighted* crack density in each layer for all the number of cycles given as input (figure 1a);
- The global elastic properties of the laminate for all the number of cycles in input (figure 1b);
- The stresses and strains in each layer at number of cycles sampled from the input (figure 1c);
- The *damage curves* (average crack density as a function of the longitudinal coordinate of the layer) for number of cycles sampled from the input, for all the layers (figure 1d).

Some examples of output results are shown in figure 1. The simulation is related to a glass/epoxy laminate with lay-up $[0/50_2/0/-50_2]_s$ as those tested in Ref. [12], under a global maximum cyclic stress of 163 MPa. Results shown in figures 1c and 1d are for the second layer of the laminate ($50_2$).

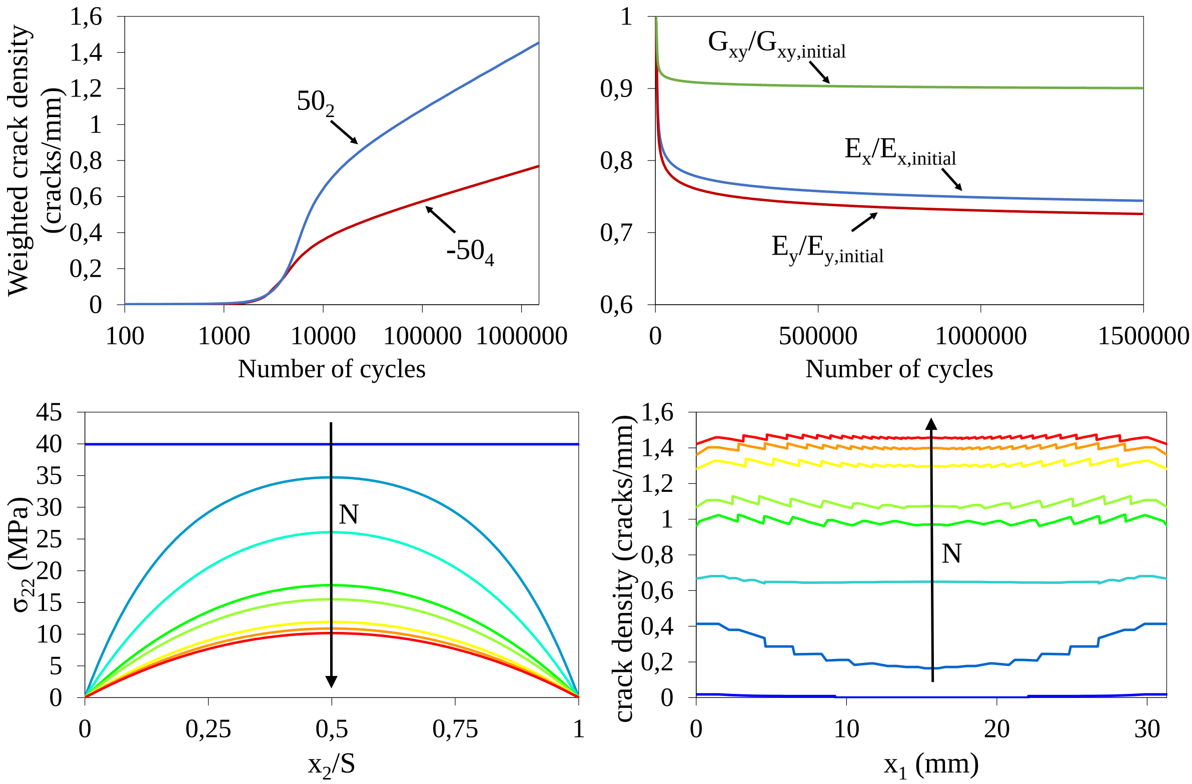


**Figure 1**: Examples of software outputs: a) *Weighted* crack density vs N, b) Elastic properties vs N, c) Stresses and strains vs $x_2$, d) *damage curves*.

## 4. Example of application

The proposed procedure is now applied to the laminates tested in Ref. [12] with lay-up $[0/50_2/0/-50_2]_s$. The laminates were tested under cyclic uniaxial load starting with six initial strain levels (0.6-1.1%). Tests were carried out in load control. In Ref. [12] the results have been presented in terms of S-N curves for the initiation of the first cracks, Paris-like curves, and weighted crack density evolution in both the +50° (thin) and the -50° (thick) layers.

According to the multiaxial condition, the LMPS parameter and the total ERR, $G_{tot}$, have been chosen as $\sigma_{eq}$ and $G_{eq}$, respectively.
In this case, to be more precise, the ERR versus crack density trends were computed by means of finite element analyses carried out in [12] and given as an input to the program. Here, the results are shown for the $50_2$ layer. The model predictions for the *weighted* crack density and $\varepsilon_{x,max}$ ranging from 0.8 % to 1.1 % are presented in figure 2 and compared to the experimental data from [12]. It can be seen that the predictions are in satisfactory agreement with experimental results.

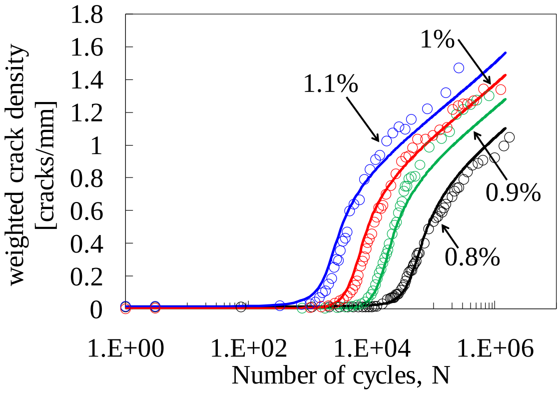


**Figure 2**: Comparison between the model predictions and the experimental results from [12]

## 5. Conclusions

A software tool has been developed to implement an analytical procedure developed by the authors for the prediction of the *weighted* crack density evolution in the off-axis layers of a general symmetric multidirectional laminate under fatigue loading. The program also implements a model for the calculation of the stiffness degradation as a function of the predicted crack density evolution, thus representing an important tool for the safe design of composite laminates against fatigue degradation. The software has been developed in the Matlab® environment and a user friendly graphic interface has been created. A comparison with experimental data revealed a satisfactory reliability of the developed model.

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