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A PREDICTION OF CRACK DENSITY IN STATIC AND IN FATIGUE, USING AN INCREMENTAL DAMAGE MODEL WITH AN OBSERVABLE VARIABLE

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ABSTRACT

One of the main challenges, which has emerged in the last couple of years for high performance industries, lies in efficiently designing lighter, less consuming structures, while ensuring optimum performances and the necessary level of safety. For these reasons, composite materials have been increasingly used, and there is now both an ecological and economic necessity of developing predictive damage models, able to provide a fatigue life estimation with a moderate complexity for laminated composites. Indeed, this could help (i) lower experimental costs, (ii) reduce design times, and (iii) achieve a fatigue life extension with the same degree of safety, through the use of appropriate safety factors. With this aim, a unified approach for both static and fatigue loadings has been developed to predict transverse matrix cracking in organic matrix laminated composites.

This approach is articulated around two parts, with a high level of interaction: the realization of a complete experimental campaign, both on academic laminates and on more complex ones with multiple off-axis plies, and the development of a predictive damage model, balancing accuracy and complexity. The material tested in this study is a laminate with an epoxy matrix and continuous carbon fibres, the IMA/M21ev. Its interfaces exhibit the particularity of being reinforced by thermoplastic nuclei, in order to limit delamination between the plies. Different stacking sequences have been manufactured, in order to lead the experimental campaign, both in static and in fatigue, with multiple objectives: the characterization of effects linked to the stacking sequence, the identification of the model's parameters, and the evaluation of its predictive abilities. Those tests were highly instrumented, with an experimental setup including Acoustic Emission sensors, Digital Images Correlation, and optic microscopy, allowing a crack density monitoring on the specimen's edge, using an automated detection tool recently developed at ONERA [1]. Moreover, 2D X-rays tomographies as well as 3D tomographies have also been performed on damaged specimens as can be seen on Figure 1, respectively at the AMADE laboratory in Girona, and at the LMPS laboratory in Saclay, in the aim of investigating the free edge effect. It has been found that after the tests, the great majority of cracks went through the entire width of the specimen, both in static and in fatigue, for quasi-isotropic (QI) and cross-plies (CP) laminates. This confirms the link between observation of cracks on the edge and the damage state, in order to go towards a fatigue lifetime prediction.

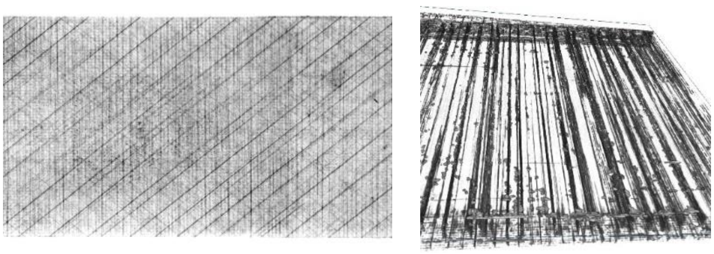

Figure 1: X-Rays on fatigue damaged QI laminate and tomography on static damaged CP laminate

The model developed in this study is derived from the works of Germain [2] in his PhD thesis, where he proposed a complete modelling at the mesoscopic scale, using two observable variables: the normalized crack density, and the microdelamination length at cracks tips. This work also follows Angrand's PhD work, where she proposed an incremental, time-based, consideration of fatigue loadings, thus enabling the description of complex loadings, closer to those encountered in the industry [3].
This model was built with the aim of maintaining a balanced complexity, and revolves around three essential steps: (i) the definition of a damage threshold, supporting the experimentally observed dependence on the ply thickness and on its position in the laminate, by using a double criteria inspired from the work of Dvorak and Camanho [4], [5]. An analysis of the experimental results also emphasized the importance of estimating the residual thermal stresses, caused by the different thermal dilatation coefficients in the oriented plies after curing. (ii) The evolution of damage, as determined by the law for both static and fatigue loadings presented below in equation (1), which leads to (iii), the attainment of a saturated damage state.

$$\dot{\bar{\rho}} = f_{stat}(\bar{\rho})g_{stat}(y)\dot{y}_{max} + f_{cycl}(\bar{\rho})g_{cycl}(y)[\langle\dot{y}\rangle_+ - \dot{y}_{max}] \quad (1)$$

Where $\bar{\rho}$ is the normalized crack density, and y is the damage driving force. First, the effect of damage on the macroscopic behaviour have not been taken into account, in order to facilitate a transition between the incremental formalism to a cyclic one, simply by integrating the aforementioned law. After identification of the model's parameters, the following results presented in Figure 2 have been obtained for a crack density prediction in the 45 and 90° plies of a QI laminate. More results will be presented in static and in fatigue on cross-plies, quasi-isotropic and complex multiaxial laminates.

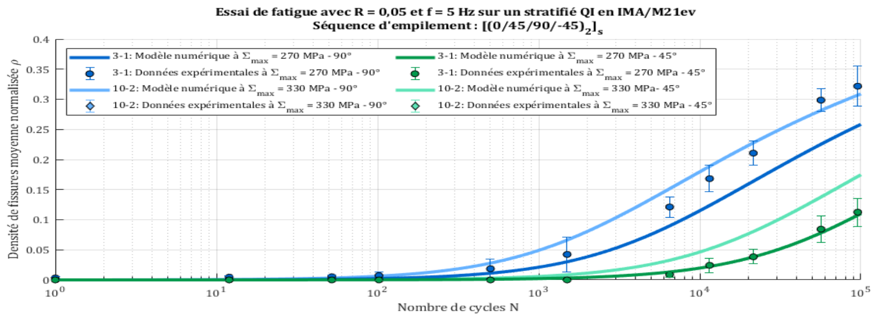

Figure 2: Example of crack density predictions with the proposed model

On the model aspect, its complete formulation, as well as its identification and predictive abilities will be presented and compared with experimental results on the different stacking sequences tested. Despite some limitations, related to the macroscopic behaviour of the laminate, which must remain reasonably linear as the thermodynamic forces are driven by the global strain, this approach has proven to be effective in describing all the constant amplitude fatigue tests performed in this work, while maintaining a low complexity. Moreover, a unified approach has been presented for both static and fatigue loadings, with the use of an observable variable, the crack density, and a formalism enabling the description of complex loadings, close to those encountered in the industry.

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