STUDY OF INTRA- AND INTER-LAMINAR DAMAGE INTERACTIONS IN LAMINATED COMPOSITES USING FINITE FRACTURE MECHANICS

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Abstract

Composite laminates are widely used in aerospace industry overall for their mass-to-performance ratio. In this context, the storage of cryogenic propellant is subject to numerous studies, in which the composite must ensure a sealing function. However, the permeability is strongly related to the damage state of the laminate and heterogeneities at micro and meso scales make their damage behavior hard to predict. Among all damage mechanisms, transverse cracks (TC) and microdelamination (MD) are particularly interesting. Indeed, their coalescence through the laminate thickness is likely to generate leakage paths. Experimental observations often show that the transverse cracking bifurcates either in microdelamination at ply interfaces or in additional transverse cracks in adjacent plies. The Finite Fracture Mechanics (FFM) demonstrated its relevance in the prediction of crack propagation but it relies on a presupposed path. Therefore, FFM is well appropriate to study the competition between potential identified cracking paths. In this context, two scenarios, microdelamination at transverse crack tips and transverse cracking in adjacent plies are studied with FFM in order to identify the preferred mechanism regarding some material properties (strength, fracture energy …) and geometrical parameters (ply thicknesses and orientations…). In addition to the cracking scenario and patern, FFM will also provide information on cracking rates with the aim of predicting the overall damage state of the laminate.

1 Introduction

In a context of lightening space launchers, the development of liquid propellant tanks in composite materials without liner is a technological challenge. The absence of a liner requires that the composite must meet the functional criteria of strength and permeability. Yokozeki et al. [1] highlights the link between the laminates damage state and its permeability, the most critical mechanisms being transverse cracking and micro-delamination (see Fig. 1). The pressurization of the tank and the cryogenic temperature of propellants favorize these types of damage. Therefore, the development of a leakage rate prediction tool, requires a detailed understanding of the damage accumulation in each ply.

The material used is a CFRP composite laminate constituted with a stack of unidirectional plies made with long carbon fibers and epoxy resin. Each ply has its own orientation defined by the fiber's direction. When a ply is loaded in the transverse direction (perpendicular to the fibers), cracks propagate along fibers and through the whole ply thickness. This can lead to microdelamination at the ply interface or it can generate multiple short cracks in the adjacent ply (see Fig.1). The complexity of the micro- and meso-structure of the composite material affects the development and the interactions of different failure mechanisms.

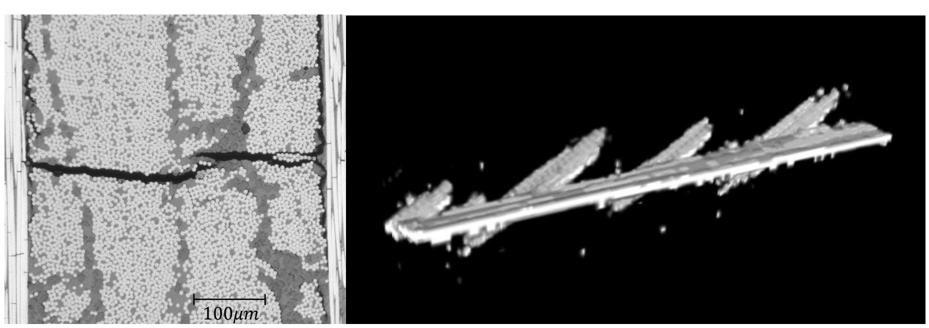

Fig.1 – Microscopy of the transverse crack and the microdelamination [2] (left) and 3D reconstruction of transverse cracks interactions obtained in tomography (right)

Over the last decade, Finite Fracture Mechanics (FFM) has been successfully used to predict critical failure loads in very different problems at different scales. It relies on Leguillon [3] and Cornetti [4] hypothesis that claim that stress and energy criterion, applied individually, represent two necessary conditions to allow a crack initiation (or propagation). The combination of these two criteria defines a sufficient condition. This model, in particular the energy criterion, relies on a presupposed crack path. Heterogen and structured materials, as laminated composites, enable oriented cracking processes which makes its good candidates for applying FFM.

2 Methodology

Finite Fracture Mechanics is based on the fact that the initiation (or the propagation) of a crack is possible if:

- The stress over the presupposed crack surface exceeds the strength of the material,
- The energy released during the cracking process should be superior or equal to the one dissipated during the propagation.

A linear finite element (FE) model is built, representing explicitly the laminate and the crack interfaces. The cell is loaded at an arbitratry level and the normal and shear stresses are calculated over the presupposed crack surface. Then the crack is progressively open and the energy released at each crack increment is computed. At each increment, the mode-mixity is also estimated by opening the crack either in pure mode I or in pure mode II. The coupled-criterion is checked afterward, from the evolution of the energy release rate and the stress, as well as proposed by [5]. Two crack patterns, microdelamination at transverse crack tips and transverse cracking in adjacent plies, were evaluated. The competition between different patterns were studied by varying strength and fracture energy. In particular, the effect of mode-mixity was highlighted. The influence of the angle between interacting plies was also analysed.

Conclusion

The application of FFM for the prediction of a preferred crack mechanism has shown its relevancy. Elastic calculations provide quickly released energies and stress fields that allow to evaluate the two required criteria for each potential crack path. Sensitivity analysis on laminate or material parameters could then be used to proposed advantagenous stacking sequences or material enhancement regarding leakage issue. Beside, this micromechanical approach will be used to introduced damage interaction laws in the meso-model developed in the research team.

Acknowledgements

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