Progressive Damage simulation in composite laminates under in-service fatigue loadings

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Progressive damage simulation in composite laminates under in-service fatigue loadings

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Abstract

A major challenge in the design and certification of aerospace composite structures consists of predicting the life and the damage tolerance under complex loading scenarios such as in-service fatigue loadings. The understanding of how damage nucleate and grow is known to be an excellent indicator of the state of the structure. Although composites are perceived to have a greater fatigue life than their metal counterparts, they experience an early degradation of the stiffness and the strength due to the accumulation of damage. Note that not the same mechanisms in static loading might be activated in fatigue loading (see figure 1).

The evolution of damage during service life of a composite laminate is usually reported as a three-stage curve, where each stage shows the presence of a different underlying mechanism causing a stiffness decrease and a process of stress redistribution. In the first stage of life, the stiffness drops fast due to the development of intralaminar matrix cracks at the off-axis plies, first in the 90^o and then in the $\pm 45^o$ plies. These cracks are not considered to be critical, but they act as stress raisers and trigger other more dangerous damage forms. Subsequent loading cycles kink these cracks into the interface developing a delamination or interlaminar crack. Then, the stiffness decreases progressively but much more slowly than the first stage of life. The last stage of fatigue life results in a sudden decrease in stiffness due to either an unstable delamination growth or a fibre fracture. The experimental observations in a notched carbon/epoxy laminate revealed that the fatigue response is strongly governed by the progressive failure of the matrix, consisting of mainly longitudinal matrix splitting cracks in 0^o plies and delamination [1–5]. These forms of damage alleviate the stress concentration at the hole and thus suppress fibre fracture. As a consequence, the laminate is significantly degraded but complete failure is never reached before 10^6 cycles even at stress levels of 75% of the ultimate strength. Indeed, fatigue damage contributes to the increase in the tensile residual strength with the number of cycles and confirms the importance of modelling sub-critical damage to predict the final failure of composite structures.

This work aims to simulate the initiation and propagation of intralaminar and interlaminar damage in quasi-isotropic open-hole carbon/epoxy laminates subjected to tension-tension fatigue loadings. The model is defined in the framework of damage mechanics and implemented as a user material subroutine in Abaqus/Explicit. The intra-ply damage constitutive model is based on the previous works of Maimí et al. [6, 7], but here extended to fatigue loadings, whereas the fatigue cohesive model by Turon et al. [8] is implemented into the explicit code following the work of González et al. [9]. Both damage models are controlled by a cycle jump strategy within the finite element code thereby improving the computational efficiency of high-cycle fatigue analysis. The numerical simulations are in good agreement with the experimental results, showing the capability of the model to predict intralaminar ply cracks, delamination and its interaction under fatigue loadings, although at this stage the result are judged qualitatively (see Figure 2).

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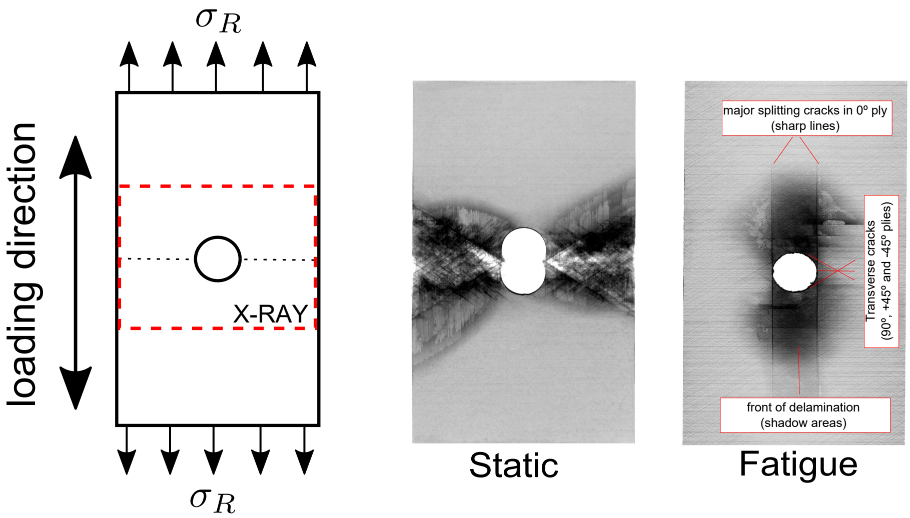

Figure 1: Failure mechanisms in a open-hole specimen subjected to static and fatigue loading (inspection by X-ray radiography)

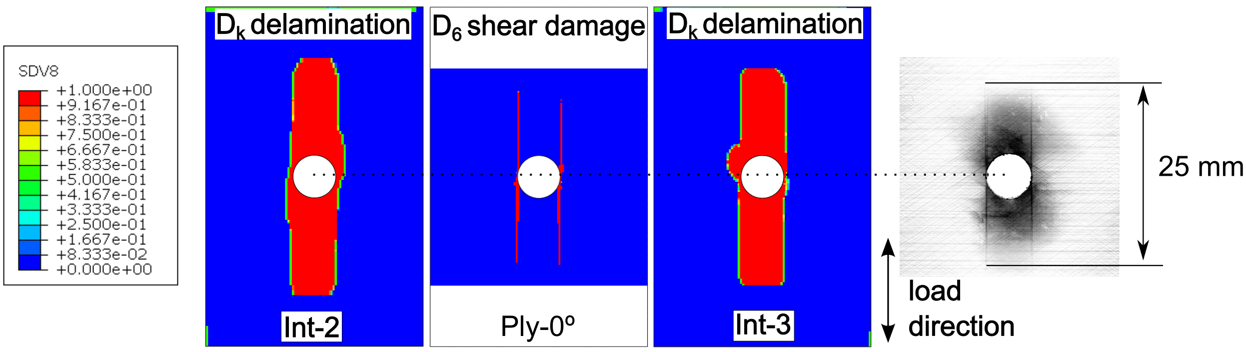

Figure 2: Comparison of damage patterns in between the numerical model and experiments (fatigue loading of 75% static strength and $1.5 \cdot 10^6$ cycles)