



Aalborg Universitet

AALBORG UNIVERSITY  
DENMARK

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

Llobet, J.; Maimi, P.; Turon, A.; Bak, Brian Lau Verndal; Lindgaard, Esben; Essa, Y.; Escalera, F. M. de la

*Published in:*

In Proc. of Society of Advancement of Material and Process Engineering (SAMPE 2018)

*Publication date:*  
2018

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Llobet, J., Maimi, P., Turon, A., Bak, B. L. V., Lindgaard, E., Essa, Y., & Escalera, F. M. D. L. (2018). Progressive Damage simulation in composite laminates under in-service fatigue loadings. In *In Proc. of Society of Advancement of Material and Process Engineering (SAMPE 2018)*

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

### Take down policy

If you believe that this document breaches copyright please contact us at [vbn@aub.aau.dk](mailto:vbn@aub.aau.dk) providing details, and we will remove access to the work immediately and investigate your claim.

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

J. Llobet<sup>a</sup>, P. Maimí<sup>a</sup>, A. Turon<sup>a</sup>, B.L.V. Bak<sup>b</sup>, E. Lindgaard<sup>b</sup>, Y. Essa<sup>c</sup>, F. M. de la Escalera<sup>c</sup>

<sup>a</sup>AMADE, Department of Mechanical and Construction, University of Girona, Campus Montilivi, E-17003 Girona, Spain

<sup>b</sup>Department of Materials and Production, Aalborg University, Fibigerstraede 16, Aalborg East, Denmark

<sup>c</sup>AERNNOVA Engineering, Structural Integrity Department, Manoteras avenue 20, E-28050 Madrid, Spain

---

## 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  $90^\circ$  and then in the  $\pm 45^\circ$  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  $0^\circ$  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).

---

## References

- [1] B. Aidi, M. K. Philen, S. W. Case, Progressive damage assessment of centrally notched composite specimens in fatigue, *Composites Part A: Applied Science and Manufacturing* 74 (2015) 47–59.

- [2] F. Aymerich, S. Found, Response of notched carbon/PEEK and carbon/epoxy laminates subjected to tension fatigue loading, *Fatigue & Fracture Of Engineering Materials & Structures* (2000) 675–683.
- [3] O. J. Nixon-Pearson, S. R. Hallett, P. W. Harper, L. F. Kawashita, Damage development in open-hole composite specimens in fatigue. Part 1: Experimental investigation, *Composite Structures* 106 (2013) 890–898.
- [4] O. J. Nixon-Pearson, S. R. Hallett, An investigation into the damage development and residual strengths of open-hole specimens in fatigue, *Composites Part A* 69 (2015) 266–278.
- [5] F. Llobet, J., Maimí, P., Turon, A., Bak, B. L. V., Lindgaard, E., Essa, Y., Martin de la Escalera, Progressive damage modelling of notched carbon/epoxy laminates under tensile fatigue loadings, in: 18th European Conference of Composite Material - ECCM18, 2018.
- [6] P. Maimi, P. P. Camanho, J. A. Mayugo, C. G. Dávila, A continuum damage model for composite laminates: Part I Constitutive model, *Mechanics of Materials* 39 (10) (2007) 897–908.
- [7] P. Maimi, P. P. Camanho, J. A. Mayugo, C. G. Dávila, A continuum damage model for composite laminates: Part II Computational implementation and validation, *Mechanics of Materials* 39 (10) (2007) 909–919.
- [8] A. Turon, B. L. V. Bak, E. Lindgaard, C. Sarrado, E. Lund, Interface elements for fatigue-driven delaminations in advanced composite materials, in: S. Camanho, P.P., Hallett (Ed.), *Numerical Modelling of Failure in Advanced Composite Materials*, Woodhead Publishing Series in Composite Science and Engineering, 2015, Ch. 3, pp. 73–91.
- [9] E. V. Gonzalez, P. Maimi, A. Turon, P. P. Camanho, J. Renart, Simulation of delamination by means of cohesive elements using an explicit finite element code, *CMC-Computers Materials & Continua* 9 (1) (2009) 51–92.

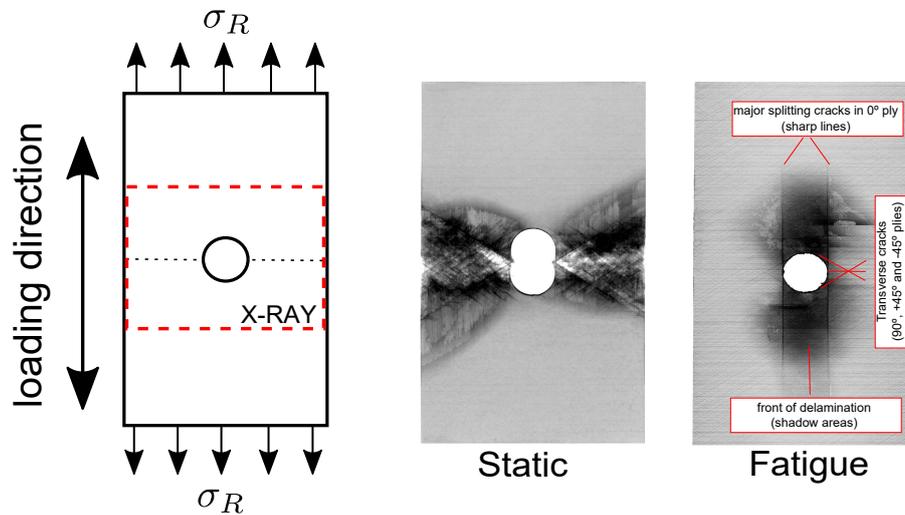


Figure 1: Failure mechanisms in a open-hole specimen subjected to static and fatigue loading (inspection by X-ray radiography)

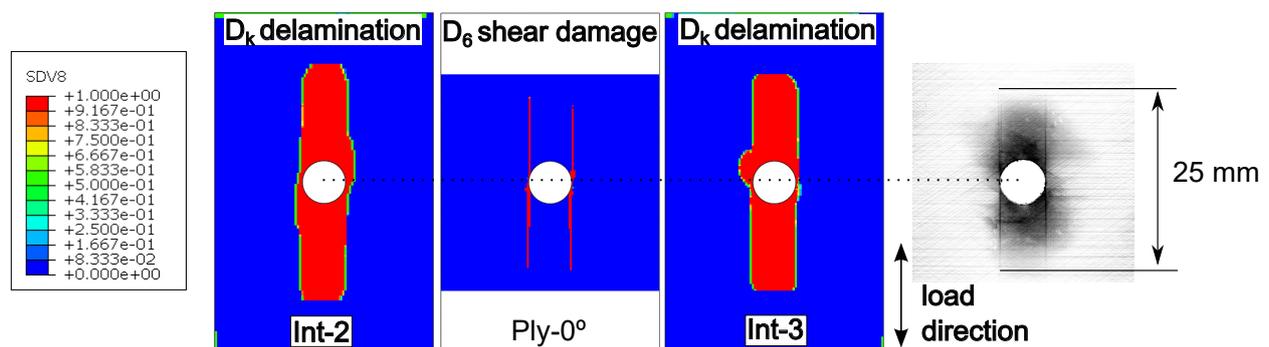


Figure 2: Comparison of damage patterns in between the numerical model and experiments (fatigue loading of 75% static strength and  $1.5 \cdot 10^6$  cycles)