PROGRESSIVE DAMAGE MODELLING OF NOTCHED CARBON/EPOXY LAMINATES UNDER TENSILE FATIGUE LOADINGS

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Abstract

This work aims to simulate the initiation and propagation of intralaminar and interlaminar damage in 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. [1, 2], but extended to fatigue loadings, whereas the fatigue cohesive model by Turon et al. [3] is implemented into the explicit code following the work of González et al. [4]. 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 experimental observations revealed that the fatigue response of notched carbon/epoxy laminates is strongly governed by the progressive failure of the matrix, consisting of mainly longitudinal matrix splitting in 0º plies and delamination. 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.

The numerical results show the model's capability to predict splitting cracks, delamination and its interaction under fatigue loadings, although at this stage the capability is only judged qualitatively.

1. Introduction

Composite materials experience a degradation of the stiffness and the strength due to the accumulation of damage during service life. Typically, the damage development of a conventional notched quasi-isotropic laminate is described by a three-stage curve [5]. The first stage corresponds to the presence of matrix cracking in the 90º plies. Stage II shows the formation of splitting cracks in 0º and ±45º plies along with some delaminations. Within this stage the stiffness decreases progressively until reaching stage III where unstable delamination growth or fibre fracture occurs (see figure 1).

There is experimental evidence that the presence of matrix splitting in 0º plies controls the fatigue response of carbon/epoxy material systems, as can be seen in the X-ray images of figure 1 [6–9]. The splitting crack progresses steadily and induces a delamination crack in the adjacent plies that grows at a similar rate. These fatigue mechanisms reduce the stress concentration around the hole thus avoiding fibre fracture. Indeed, the tensile residual strength after fatigue damage increases with the length of the splitting crack and becomes higher than the static open-hole ultimate strength (OHT) [7]. Although the material does not experience complete failure before 10^6 cycles even at stress levels of 75% OHT, the laminates stiffness is significantly degraded thereby compromising the structural integrity.

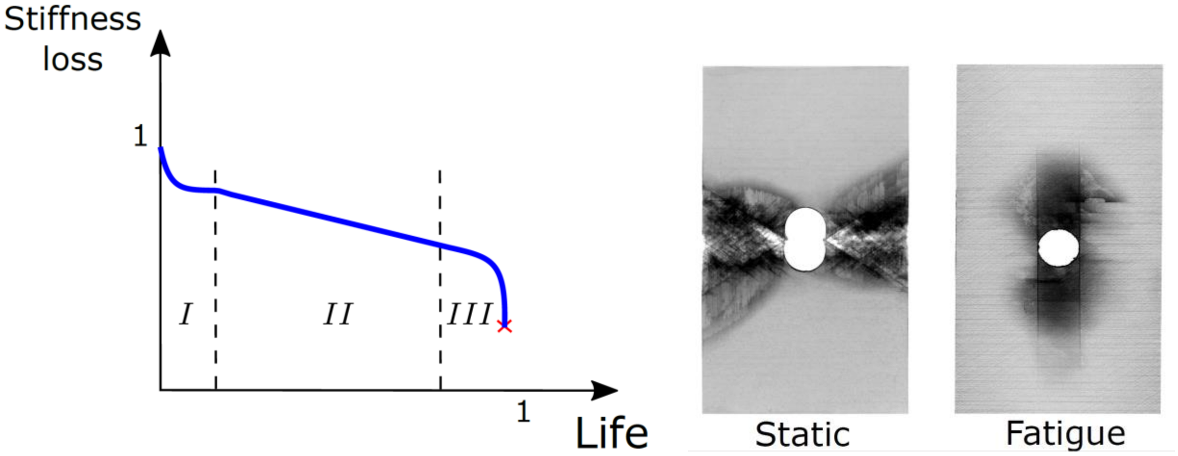

Figure 1. Damage mechanisms in open-hole specimens under static and fatigue loadings.

This work focus on the simulation of delamination and matrix splitting in open-hole carbon/epoxy laminates under fatigue loading. In order to do that, the continuum damage model (CDM) from Maimí et al. [1, 2] is extended to fatigue loadings and is coupled with the fatigue model from Turon as two user-material subroutines for Abaqus\Explicit (VUMAT). This study is also devoted to explore the capabilities and limitations of CDMs on the modelling of splitting cracks as well as the interaction with delamination cracks represented by the Cohesive Zone Model (CZM).

2. Experimental work

The material under study is a carbon/epoxy pre-preg of 0.184 mm nominal ply thickness. The open-hole specimen dimensions are 250 x 32 x 4.4 mm (diameter of the hole, 2R=6.3 mm) with a laminate stacking sequence of $[90\ {+45}\ {-45}\ 0]_{3s}$. Glass-fibre tabs were used to avoid gripping damage during fatigue testing.

The experimental campaign consists of static and fatigue tests at different severities (or stress levels). All tests were performed using an universal servo-hydraulic test machine 810 MTS at AMADE research lab. Static tests are controlled by displacement and fatigue tests are run in force control. The average strains are measured by a local axial extensometer in the gage section including the hole. The damage patterns were monitored by means of enhanced X-ray radiography.

3. Constitutive model: static and fatigue damage

The fatigue model consists of a mesoscale CDM, based on the work of Maimí [1, 2], to describe intralaminar damage but herein extended to account for fatigue loadings, and coupled with the fatigue CZM from Turon et al. [3] to represent interlaminar damage. The two models are synchronized by the Abaqus user subroutine VEXTERNALDB and a cycle jump strategy.

The CDM model considers four intralaminar failure modes: fibre tensile failure, fibre compression failure, matrix tensile failure and matrix compression failure according to LARC03 criteria. Five cohesive laws are defined to describe the static damage evolution in terms of the corresponding dissipated fracture energy. The energy dissipated for each damage mechanism is regularized by the crack-band method in order to guarantee mesh independency. Then, three damage variables are computed after material localization, D1 (fibre damage), D2 (transverse matrix damage) and D6 (shear matrix damage).

The static CZM by Turon et al. [10], implemented as a VUMAT subroutine in the work of González et al. [4], is taken as the baseline code in which the model of Turon et al. [3] is implemented.

3.1. Intralaminar fatigue damage

Fatigue loadings may induce different forms of damage into the laminate plies; from distributed fibre damage in the form of fibre/matrix debonding to localized shear matrix cracks in off-axis plies where off-axis plies refer to 90º and ±45º plies. Emphasis is placed on the modelling of matrix splitting in 0º plies. It is known that splitting cracks develop and grow under dominant mode II crack growth due to a high in-plane shear stress.

Different CDMs have been successfully used to predict splitting cracks in notched specimens under static loadings. Despite these advances, several limitations when modelling localized matrix cracks using continuum theories have been identified [11–15]:

- Iarve [16] showed that spurious stress transfer across the crack faces occurs when the mesh is not aligned with the fibre direction. Then, stress redistribution is not correctly captured in the vicinity of the hole. It is strongly recommended to align the mesh with the fibre direction and use reduced-integration elements to alleviate the tendency for locking [11, 15].
- The inability of local CDMs to represent localized shear fracture bands due to the homogenization within fibre and matrix at the mesoscale level [11, 14].
- Although CDMs are enhanced with crack-band method to ensure mesh independency, there exists a tendency for damage localization along the mesh direction [11].

In this regard, Nixon-Pearson and co-workers [8, 17, 18] inserted cohesive elements at the potential matrix crack sites to represent splitting cracks. However, this approach requires additional meshing effort and crack locations must be predefined.

In this study, the splitting cracks are represented within the continuum model. It is assumed that an intralaminar matrix crack grows with the same rate as an interlaminar crack, thus the same experimental Paris laws are used. The fatigue damage growth rates (dD/dN) are related to the crack growth rates (da/dN) as in Turon's fatigue model [3]. The fatigue damage evolution functions governing the growth of splitting cracks are defined as, dD_2/dN for mode I, and dD_6/dN for mode II crack growth.

3.2 Interlaminar fatigue damage

The open-hole experiments showed a strong interaction between the splitting cracks and delamination during the entire fatigue degradation process. Several fatigue CZMs are available in the literature [19–21]. Turon's model is used herein. Despite the limitations of local or pointwise interlaminar fatigue models such as Turon's model [3, 19], its implementation as a user material subroutine is straightforward compared to the non-local ones (i.e [22]), where the J-integral is used to consistently link the Paris law with a local damage rate model.

All the interlaminar fracture characterization to obtain the mode I (DCB), mode II (ENF) and mixed-mode (MMB) Paris laws have been performed at AMADE research lab [23].

3.3 Strategy to implement the fatigue model in Abaqus Explicit

Figure 2 shows an example of a possible scenario of loading cases that can be applied to a composite structure. Different load steps can be applied such as static, dynamic, or fatigue loading steps. The fatigue step requires two stress levels and the number of cycles in which these two stress levels will be repeated. Since performing a cycle-by-cycle simulation is computationally impractical, a cycle jump approach is used within the finite element code. This approach is widely used in high-cycle fatigue analysis [24], especially when large-scale structures are assessed. The cycle jump algorithm is prepared to be executed on HPC environment running on multiple cores.

The fatigue step consists of a first cycle simulated in real-time where the internal static variables may increase due to fatigue stress levels. Then, a second real-time cycle is applied where the maximum and minimum local stresses are computed. Once the maximum and minimum stresses are known for each material point, a cycle jump is computed. The cycle jump is determined as to guarantee that the damage increase in the critical element is less than a predefined limit. This limit must be relatively small since the exact damage increment per cycle jump (dD/dN) is not known a priori. Finally, the fatigue damage variables are increased according to the cycle jump and the process is repeated.

The strategy implemented allows to account for the effect of the local stress ratio at the material points. As an alternative method, the envelope approach [3, 22] may also be used by simply changing the load waveform in the fatigue step and defining a constant stress ratio. For the sake of simplicity the envelope approach is used here.

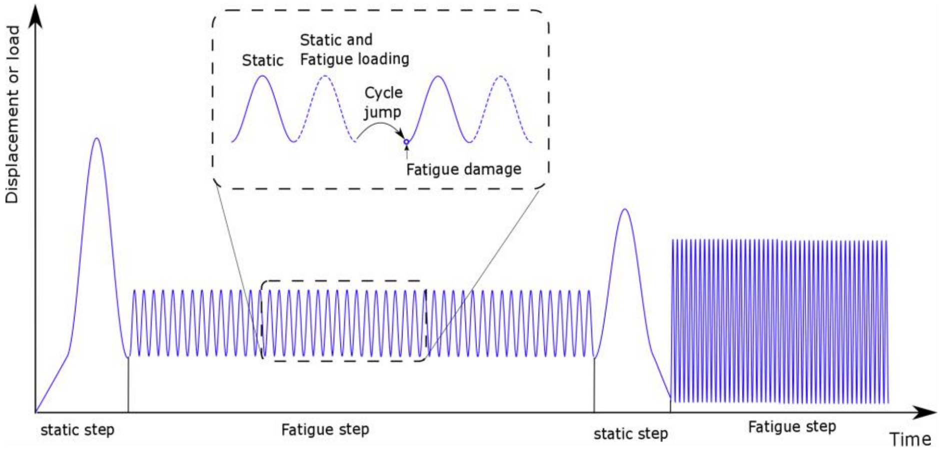

Figure 2. Cycle jump strategy in explicit finite element code.

4. Numerical model

The fatigue simulations are performed with a simplified FE model as shown in figure 3. The model assumes that the behaviour of 90º and ±45º (off-axis) plies is linear elastic (neither damage nor plasticity), whereas the constitutive law of 0º plies is defined by the intralaminar damage model. Then, the off-axis are blocked together as a single shell element and a composite layup. Cohesive elements are inserted in the interfaces between the on-axis plies with damage. Reduced-integration shell elements (S4R) and standard Abaqus cohesive elements (COH3D8) of 0.25 mm are used. Tie constraints are used to connect the structural plies and their respective interfaces. The mesh is aligned with the fibre direction.

The boundary conditions at the left end of the specimen are fixed (Ux = Uy = 0). At the right end, the specimen is constrained in the transverse direction (Uy = 0) and the enforced displacement is defined in longitudinal directional (Ux). Symmetry boundary conditions (Uz = Rx = Ry = 0) are used by taking advantatge of the symmetrical lay-up (through-the-thickness direction).

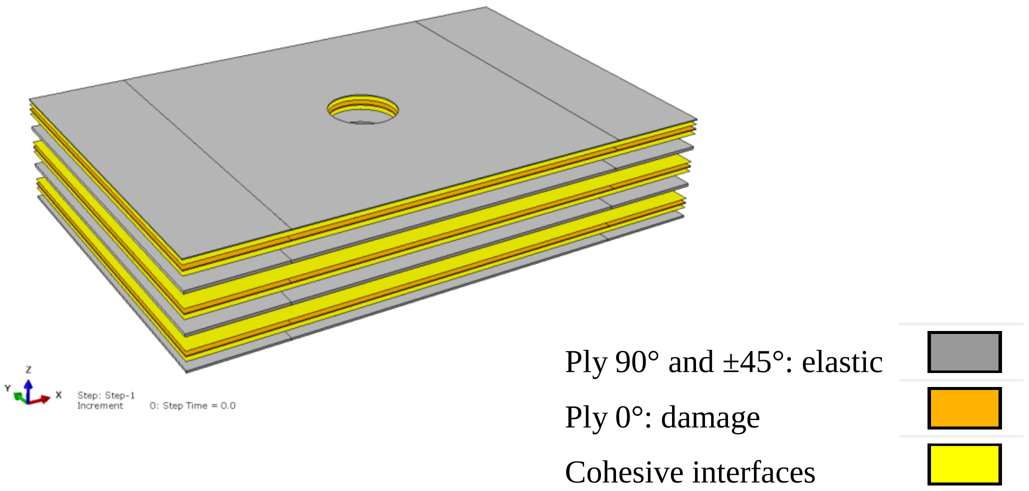

Figure 3. Simplified finite element model of [90 ±45 0]$_{3s}$ with through-the-thickness symmetry conditions.

4. Results

A fatigue analysis at a stress level of 75% of the OHT and constant stress ratio R = 0.1 is performed. It is emphasized that the model is not completely validated at this stage and the accuracy of the simulations is judged qualitatively. Figure 4 shows the fatigue damage developed in the form of splitting cracks and delamination. Despite the simplifications done in the numerical model, the damage patterns at similar cycle intervals are reasonably comparable.

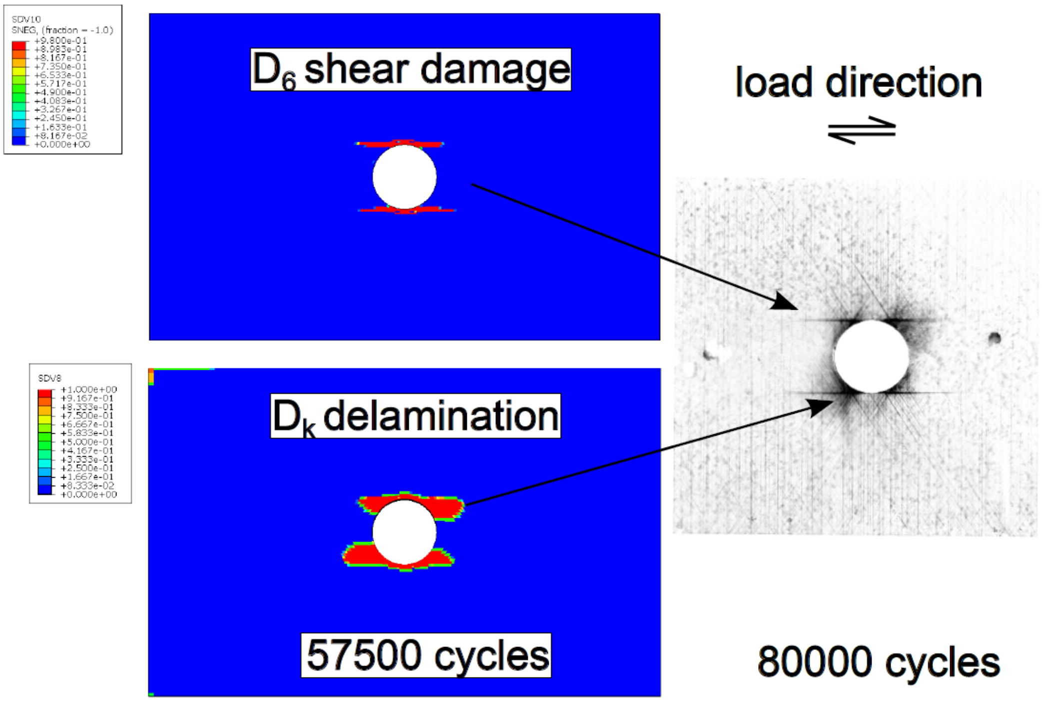

Figure 4. Numerical results vs. experiments for a fatigue stress level of 75% of the OHT.

Figure 5 shows the distribution of normal stresses at the first cycle and after fatigue damage, and thus the damage mechanisms that alleviate the stresses at the notch through stress redistribution.

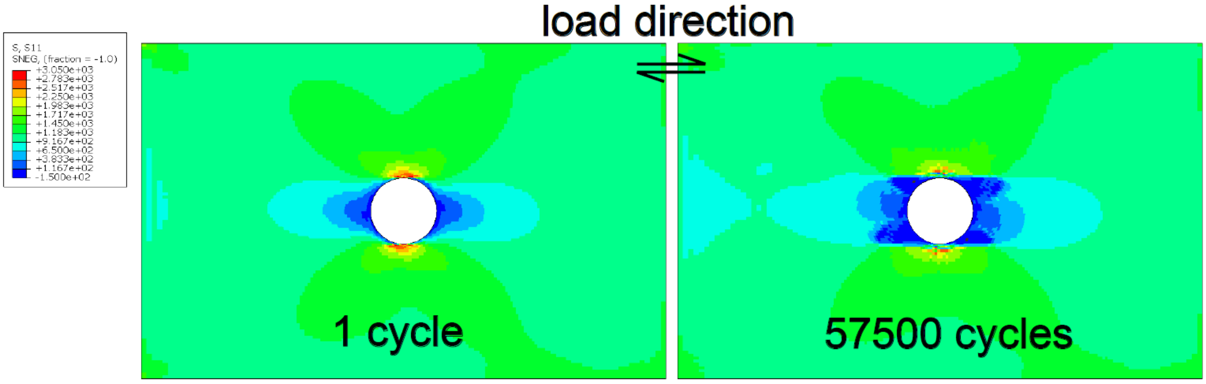

Figure 5. Normal stresses in the 0º ply at N=1 cycles and after N=57500 cycles.

5. Conclusions

A computational model has been implemented in an explicit finite element code to simulate intra- and interlaminar damage under fatigue loadings.

Within this study, a simplified finite element model has been used with the aim of exploring the capabilities of predicting splitting cracks in 0º plies, delamination, as well as its interaction. Despite the simplications done, the model is capable of capturing the main damage mechanisms in an open-hole specimen subjected to tension-tension fatigue loading.

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