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A Multiaxial Fatigue Damage Model for Composite Laminates

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This paper presents a novel damage mechanics based failure model that enables prediction of fatigue life and residual strength in composite structures under multiaxial loading. The approach herein proposed does not discretize every load cycle but instead takes an envelope loading whereby the numerical load remains constant at a maximum load level and the number of cycles is obtained from a given elapsed time defined within a pseudo-time framework. The proposed formulation is based on the smeared cracking approach accounting for damage propagation due to static and fatigue loadings. The static and fatigue damage evolution laws are defined based on the Continuum Damage Mechanics (CDM) approach and Paris-law parameters, respectively. Furthermore, the formulation combines damage mechanics and fracture mechanics within a unified approach enabling the control of the energy dissipated in each loading cycle.

Keywords: Damage Mechanics, Fracture Mechanics, Fatigue, Finite Elements

INTRODUCTION

Fibre-reinforced composites are often selected for weight-critical structural applications due to the high specific stiffness and strength that these materials provide. However, current lifetime prediction methodologies commonly employed by the aeronautical industries are based on large factors of safety that in turn leads to overdesigned structures. Furthermore, these methodologies require extensive and expensive prototype testing in order to build up design database in both coupon and component levels in order to provide acceptable lifetime prediction. Improved damage accumulation models and lifetime prediction methodologies may result in a more efficient use of these materials and in a shorter time-to-market. Within this context, this paper presents a methodology for modelling fatigue-induced damage in composite laminates under multiaxial loading at ply level.

The damage evolution law has often been written in terms of normalized stress or strain such as in Yao and Himmel (2000), Shokrieh and Lessard (2000), Paepegem and Degrieck (2001), and Wu and Yao (2010). This approaches is effective in predict the stiffness and strength degradation as well as the element fatigue life. However, they are not capable of predicting a discrete fatigue crack growth accurately. Turon et al. (2007) proposed a damage evolution formulation derived from the Paris's law described in terms of Strain Energy Release Rate (SERR) to simulate fatigue delamination in composites. Kawashita and Hallett (2012) proposed a crack-tip tracking algorithm that improved this approach eliminating the need to estimate the cohesive zone size. Despites being proposed for delamation growth, both approaches are more suitable to predict the crack growth rate than the stress or strain based one. In this present work, these approaches are used to assess the intralaminar crack growth.

In order to model fatigue driven intralaminar crack, a semi-empirical damage evolution law derived in terms of the Paris's Law parameters was incorporated into a Continuum Damage Mechanics Failure Model previously developed by (Donadon et al 2005, 2008b and Yokoyama et al 2010). The proposed failure modelling methodology enables the life prediction and residual strength of composite aerostructures. In order to show the model capabilities, numerical results for Composite Compact Tension (CT) specimens subjected to cyclic loading are presented and compared with experimental results.

DAMAGE MODEL FORMULATION

The formulation proposed to model progressive failure in composites is based on the smeared cracking approach (Donadon et al 2005, 2008b). The smeared cracking formulation relates the specific or volumetric energy, which is defined by the area underneath the stress-strain curve, with the strain energy release rate of the material. The method assumes a strain softening constitutive law for modelling the gradual stiffness reduction due to the micro-cracking process within the cohesive or process zone of the material. In order to avoid pathological problem associated with strain localization and mesh dependence during softening, the softening portion of a stress-strain curve is adjusted according to the element topology and cracking direction for each failure mode using an advanced objectivity algorithm.

Failure criteria to detect damage due to static loading

The failure criteria used to detect static damage initiation for all in-plane failure modes are all based on the maximum stress criteria and they are given in the general form as follows,

$$F_{ij}^{k}(\sigma_{ij}) = \frac{\sigma_{ij}}{S_{ij}^{k}} - 1 \geq 0 \tag{1}$$

where $F_{ij}^{k}(\sigma_{ij})$ is the failure index associated with the failure mode k and direction ij, where the superscript $k = t$ refers to failure in tension and $k = c$ refers to failure in compression and the subscripts $i = j = 1$, $i = j = 2$, and $i \neq j$ refer to the longitudinal, transverse, and shear directions, respectively. σ_{ij} is the stresses acting on each layer at the local material coordinate system and S_{ij}^{k} is the material strength.

Static damage evolution laws

The general expression proposed for the static damage evolution laws in the longitudinal and transverse directions is given as follows,

$$D_{ii}^{s}(\lambda_{ii}^{t}, \lambda_{ii}^{c}) = \lambda_{ii}^{t} + \lambda_{ii}^{c} - \lambda_{ii}^{t}\lambda_{ii}^{c} \tag{2}$$

where D_{ii}^{s} is the static damage variable for longitudinal ($i = 1$) and transverse ($i = 2$) directions, which is represented in terms of the damage parameters λ_{ii}^{k}.

$$\lambda_{ii}^{k} = \frac{2G_{ii,c}^{k}}{2G_{ii,c}^{k} - S_{ii}^{k} l^{*} \varepsilon_{ii,0}^{t}} \left(\frac{\varepsilon_{ii}^{k} - \varepsilon_{ii,0}^{k}}{\varepsilon_{ii}^{k}} \right) \tag{3}$$

where the superscript $k = t$ refers to tensile loading induced damage and $k = c$ refers to compression loading induced damage. The static damage evolution law in shear is,

$$D_{12}^{s} = \frac{2G_{12,c}}{2G_{12,c} - S_{12} l^{*} \gamma_{12,0}} \left(\frac{\gamma_{12} - \gamma_{12,0}}{\gamma_{12}} \right) \tag{4}$$

The values for both functions $\lambda_{ii}^{k}, D_{12}^{s} \in [0,1]$. $G_{ii,c}^{k}$ is the intralaminar fracture toughness, ε_{ii}^{k} refer to the nominal local strains in the longitudinal ($i = 1$) and transverse ($i = 2$) directions and γ_{12} refers to in-plane shear strain direction. The subscript 0 indicates the damage on-set value. In order to account for damage irreversibility effects $\varepsilon_{ii}^{k} = \max\left[\left| \varepsilon_{ii}^{\max}(t) \right|, \varepsilon_{i,0}^{k} \right]$ where $\varepsilon_{ii}^{\max}(t)$ is the maximum achieved strain in the strain versus time history. The characteristic length l^{*} is used for mapping the material process (or microcracking) zone into the finite element mesh. For fibre failure modes l^{*} is computed in terms of the isoparametric coordinates (ξ_{l}, η_{m}) for each integration point m according to the following expression,

$$l^{*}(\xi_{m}, \eta_{m}) = \left(\sum_{l=1}^{n_c} \left[\frac{\partial N_{l}(\xi_{m}, \eta_{m})}{\partial x} \cos(\theta_{m}) + \frac{\partial N_{l}(\xi_{m}, \eta_{m})}{\partial y} \sin(\theta_{m}) \right] \phi_{l} \right)^{-1} \tag{5}$$

where $\theta_{m} = \theta_{1}$ being θ_{1} the longitudinal orientation angle for each integration point and $\theta_{m} = \theta_{1} + 90^{0}$ for failure in the transverse direction. For four nodes shell elements $n_{c} = 4$, $N_{l}(\xi_{m}, \eta_{m})$ are bi-linear interpolation functions and ϕ_{l} is defined as crack band discontinuity function. Details about the derivation of the expression for the characteristic length for orthotropic smeared cracking modes can be found in Donadon et al (2008b).

Fatigue damage evolution laws

Due to the dynamic nature of the cyclic loading, it is more convenient to define the fatigue damage evolution law in the incremental form. The fatigue damage increments ΔD_{ii}^{f} are defined in terms of the crack growth rates $\frac{da_{ii}}{dn}$ given as follow,

$$\Delta D_{ii}^{f} = \frac{\left(1-D_{ii}^{s}\right)}{l^{*}} \frac{da_{ii}}{dn} \Omega \Delta t \tag{6}$$

where W is a numerical frequency associated with the number of cycles required to represent the actual loading spectrum as an equivalent quasi-static constant load in the pseudo-time domain. The total fatigue damage laws are computed in terms of their increments as,

$$D_{ii}^{f}\left(n_{k+1}\right) = D_{ii}^{f}\left(n_{i}\right) + \Delta D_{ii}^{f} = D_{ii}^{f}\left(n_{k}\right) + \frac{\left(1-D_{ii}^{s}\right)}{l^{*}} C_{ii}\left[\left(1-R^{2}\right)G_{ii,\max}^{t}\right]^{m_{ii}} \Omega \Delta t \tag{7}$$

where n_k is the number of cycles at increment k, n_{k+1} is the number of cycles at the subsequent increment, R is the ratio of maximum load to minimum one ($R = P_{\max} / P_{\min}$), C_{ij} and m_{ij} are the Paris law parameters obtained from fatigue tests performed in the local ply directions, *i=1,2,* using pre-cracked Compact Tension (CT) specimens. $G_{ii,\max}^{t}$ is the tensile intralaminar strain energy release rate (SERR) associated with the maximum load level $P_{\max}$.

Stress degradation procedure

The resultant degraded stresses at ply level are given by

$$\begin{Bmatrix} \sigma_{11}^{d} \\ \sigma_{22}^{d} \\ \tau_{12}^{d} \end{Bmatrix} = \begin{bmatrix} (1-D_{11}^{S}(\lambda_{11}^{t},\lambda_{11}^{c})) & 0 & 0 \\ 0 & (1-D_{22}^{S}(\lambda_{22}^{t},\lambda_{22}^{c})) & 0 \\ 0 & 0 & (1-D_{12}^{S}(\gamma_{12})) \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} - \begin{bmatrix} (1-D_{11}^{f}(n)) & 0 & 0 \\ 0 & (1-D_{22}^{f}(n)) & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} S_{11}^{t} \\ S_{22}^{t} \\ S_{12} \end{Bmatrix} \tag{8}$$

where

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} = \frac{1}{(1-\nu_{12}\nu_{21})} \begin{bmatrix} E_{11} & \nu_{12}E_{22} & 0 \\ \nu_{21}E_{11} & E_{22} & 0 \\ 0 & 0 & (1-\nu_{12}\nu_{21})\mu_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} \tag{9}$$

NUMERICAL SIMULATIONS

The proposed model has been implemented as a user-defined material model within S4R shell elements available in ABAQUS/Explicit finite element code. In order to validate the proposed model, simulations for a typical CT specimen tested under cyclic loading were performed. The predicted results were compared with experimental results. The tested specimens had total thickness of 4.05 mm, with dimension depicted in Fig. 1 (A), initial crack length a_0=21.2 mm, $[0^o]_{9s}$ lay-up made of plain weave woven fabric plies, with mechanical properties listed in Table 1. The FE model is presented in Figure 1 (B). The virtual specimen was loaded under force control with a maximum load level $P_{\max}$ =3.8 kN and R=0.16 in the weft direction, accordingly to the average loading conditions applied experimentally.

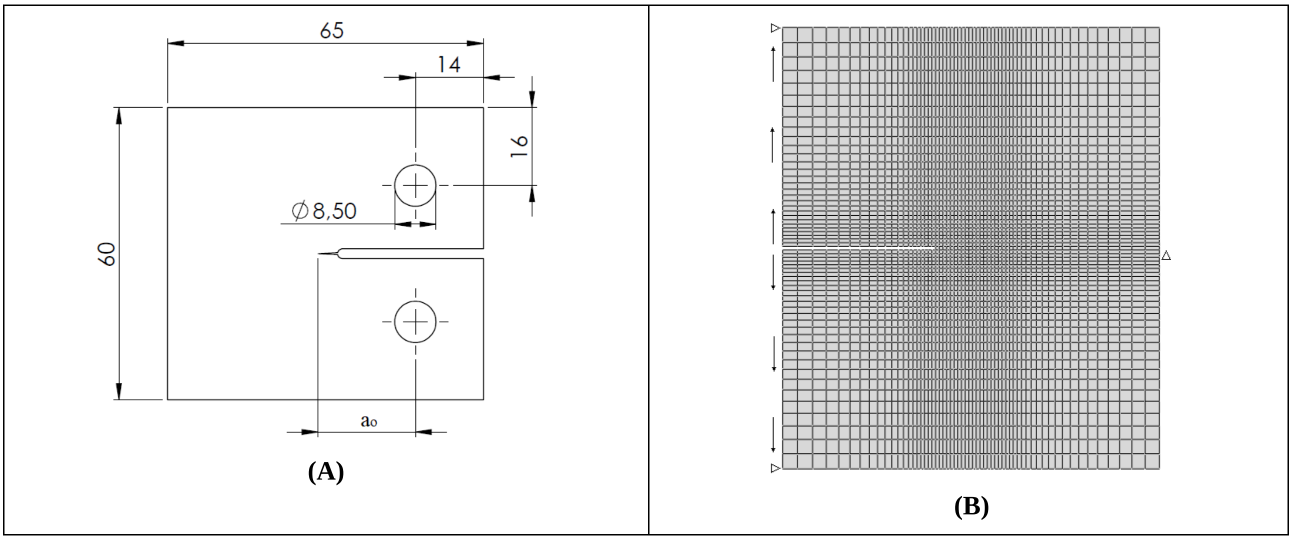

Figure 1 – CT specimen configuration: (A) specimen dimensions (*in mm*), (B) FE Model

Table 1 – Woven ply properties

Mechanical Properties			
Young's modulus - warp direction	E_{11}	58.64	GPa
Young's modulus - weft direction	E_{22}	58.64	GPa
In-plane shear modulus	μ_{12}	1.4	GPa
In-plane Poisson's ratio	ν_{12}	0.042	-
Intralaminar Fracture Toughnesses	$G^t_{11,c} = G^t_{22,c}$	123.05	kJ/m^2
Intralaminar Tensile Strengths	$S^t_{11,c} = S^t_{22,c}$	767.25	MPa

Before simulating the crack propagation event, static simulations were carried out for different crack lengths to compare the predicted compliance with the experimental one. Figure 2 shows the elastic compliance curve obtained from the experimental data, as function of crack length, along with the numerical compliance of the FE model used to represent the specimens under static loading. The curves show good agreement with each other, indicating that the model can accurately predict the elastic behaviour.

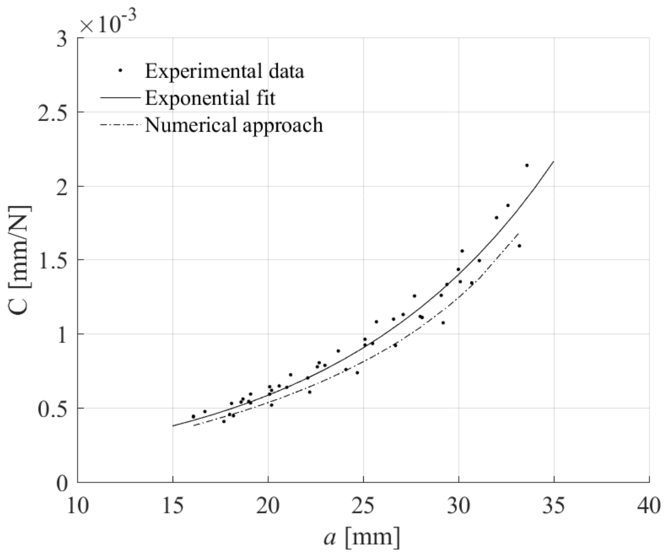

Figure 2 – Comparison between predicted and experimental compliance curves

In order to assess the proposed model's accuracy in predicting fatigue crack propagation, simulations for a typical CT specimen tested under cyclic loading were performed. Figure 3 shows four time-frames of the fatigue damage evolution, where the crack advance can be observed. In this figure, the mode I opening stress field around the crack tip for different crack length is presented. A comparison between numerical predictions and experimental results in terms of Paris plots is presented in Fig. 4, where the predictions obtained using the proposed model agree remarkably well with experimental results.

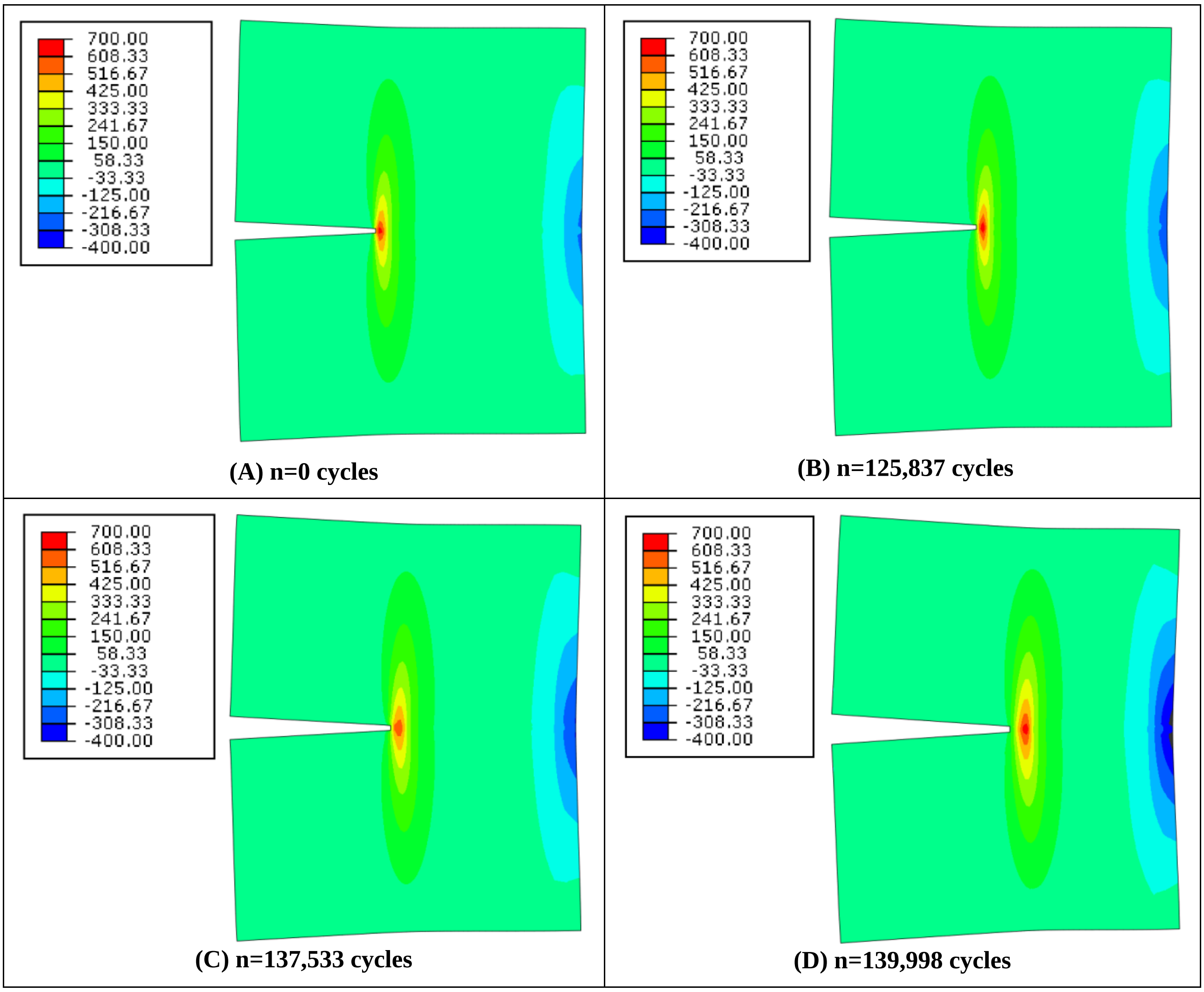

Figure 3 – Predicted crack growth stress pattern for mode I

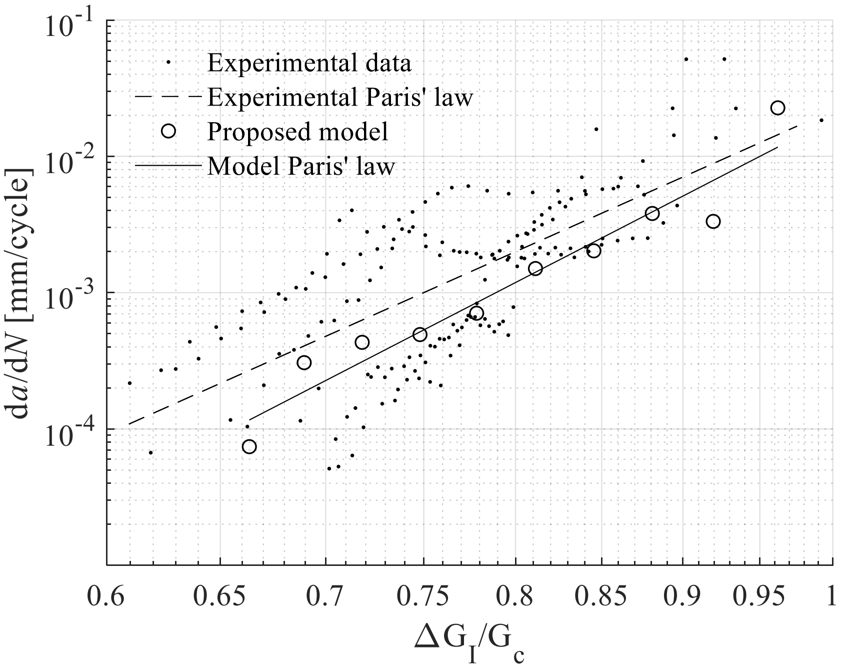

Figure 4 – Comparison between predicted and experimental Paris Law plots

CONCLUSIONS

A detailed formulation for intralaminar damage modelling in composite laminates subjected to static and fatigue loading conditions has been presented and discussed in this work. The prediction of static damage initiation onset is based on maximum stress-based criteria. Damage progression is predicted within an energy-based framework by combining damage mechanics and fracture mechanics approaches within an unified way by using the smeared cracking approach. Fatigue driven intralaminar damage was modelled by combining the static damage with a semi-empirical damage evolution law derived in terms of the Paris Law parameters. The proposed model has been implemented into ABAQUS/Explicit FE within shell elements. Numerical predictions obtained using the proposed constitutive model were compared with experimental results for Compact Tension (CT) specimens under cyclic loading. A very good correlation between numerical predictions obtained using the proposed damage model and experimental results was found in terms of damage initiation and damage propagation for typical coupons subjected to static and fatigue loading conditions.

The proposed damage model seems to be a robust and reliable design tool that enables the prediction of static and fatigue-driven delamination in composite aerostructures. It can also be easily combined with interlaminar damage model enabling life prediction and residual strength of composite aerostructures. The model proposed herein will integrate a virtual testing platform under development by the Composite Research group at ITA.

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