Numerical Simulations and Experimental Investigations on Quasi-Static and Cyclic Mixed Mode Delamination of Multidirectional CFRP Laminates

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Keywords: *Mixed Mode Bending, Cyclic Delamination, CFRP*

Abstract

This paper focuses on quasi-Static and cyclic mixed mode delamination in multidirectional composite laminates both numerically, via numerical simulations, and experimentally, via mixed mode bending experiments. The numerical model consists of individual damageable layers (lamina) and bilinear interface elements subjected to mixed mode bending. When subjected to cyclic delamination, the interfacial tractions must be degraded in each subsequent un-loading/ re-loading cycle. The amount of this degradation is specified by the cyclic damage parameter, the evolution law of which is based on the cyclic delamination crack growth rate. The numerical simulation, with the implemented constitutive interface model, reproduces the experimental results successfully and with minor error for both quasi-static and cyclic cases.

1 Introduction

The structural applications of Carbon Fibre Reinforced Plastic (CFRP) composites are gradually expanding in aerospace industry as a result of their outstanding mechanical properties, when especially cyclic loading is of primary concern. Fiber reinforced composites often exhibit complex failure mechanisms as an interaction of intra-laminar damage modes such as matrix cracking and fiber rupture and inter-laminar damage modes, predominantly delamination. Typically, delamination failures initiate and propagate under mixed mode effect of normal and shear stresses. Therefore, mixed mode delamination failure in fibrous composites has been one of the major issues being studied extensively in recent years. In this scope, the development of predictive, reliable and robust numerical and experimental analysis tools for quasi-static or cyclic mixed mode delamination of CFRPs is the major focus of this work. Accordingly, quasi-static and cyclic mixed mode delamination failure in multidirectional CFRP laminates are analyzed using fracture experiments and finite element (FE) simulations.

2 Interface Element Formulation

One of the most appealing techniques that can be used for FE simulation of delamination initiation and propagation in composites is the cohesive zone approach [1-3]. The cohesive zone approach adopted in this work makes use of interface finite elements incorporating a cohesive mixed-mode damage model. The zero thickness 8 node cohesive elements, implemented as a user element subroutine, are mainly based on the constitutive model suggested by Turon et al [3]. The relationship between the vector of interface tractions ($\boldsymbol{\tau}$) and relative displacements ($\boldsymbol{\delta}$) can be written as

$$\boldsymbol{\tau} = \left(\begin{pmatrix} (1-d)K & 0 & 0 \\ 0 & (1-d)K & 0 \\ 0 & 0 & (1-d)K \end{pmatrix} + \begin{bmatrix} 0 \\ 0 \\ dK\,H(-\delta_n) \end{bmatrix} \right) \boldsymbol{\delta} \quad (1)$$

K stands for the initial stiffness bonding both faces of the interface element together before any initiation of damage. H stands for the Heaviside function (H (x)=1 if x ›0), which panelizes compressive direct strains in order to avoid the interpenetration of the interface surfaces. The damage parameter, *d*, governs the softening behaviour of the interface and it increases from 0 (no damage) to 1 (complete separation) for monotonous load progression. As subjected to cyclic loading, the constitutive law of the interface element must be reformulated to account for subcritical damage accumulation and stiffness degradation within subsequent unloading-reloading steps [3-5]. According to [3-5] the degradation of the interface stiffness, *K*, or the evolution of the damage parameter, *d*, per cycle must be defined explicitly in order to degrade the mentioned tractions or interfacial strengths in each unloading- reloading step. The followed numerical approach in this work incorporates the interface formulation suggested by Turon et al. [3] for modelling the mixed mode delamination crack growth under cyclic loading. The fatigue damage evolution law (Equation 2) is a cohesive law that links fracture and damage mechanics to establish the evolution of the damage variable, *d*, in terms of the crack growth rate *dA/dN* or energy release rate, ΔG.

$$\frac{\partial d}{\partial N}=\begin{cases}\frac{1}{A_{cz}}\frac{(\delta_m^f(1-d)+d\delta_m^0)^2}{\delta_m^f\delta_m^0}C\left(\frac{\Delta G}{G_c}\right)^m & G_{th}<G_{max}<G_c\\ 0 & 0\end{cases} \qquad (2)$$

C, m, and G_{th} are Paris plot parameters [6] that are obtained by plotting ∂a/∂n versus cyclic variation in the energy release rate, ΔG, on log-log scale. G_c is the total mixed mode fracture toughness under a specific mode ratio. δ_m^0 stands for delamination onset, and δ_m^f, for final separation in the interface element [3].

3 Numerical Model and MMB Experiments

3.1 Quasi-static MMB

The numerical model of the laminate is described as an assembly of individual layers and interface elements. Each individual ply is assumed as an orthotropic homogenized continuum under plane stress, permitting the modelling of damage initiation in each ply under the combination of longitudinal, transverse, and shear stress states. The interface elements, the constitutive behaviour of which is implemented as a user element routine in ABAQUS, are represented via the cohesive zone concept with bilinear and exponential softening laws. The numerical model is able to successfully capture the experimentally observed effects of fibre angle orientations and variable stacking sequences on the global load-displacement response (Fig.1) and mixed mode inter-laminar fracture toughness of the various laminates.

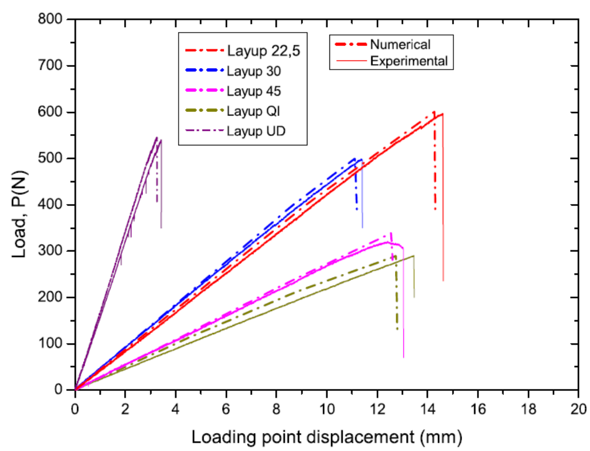

Fig. 1: Comparison of load-displacement response for different multidirectional laminates with 50% mode mixity (numerical and experimental)

3.2 Cyclic MMB

Cyclic mixed mode delamination in multidirectional composite laminates subjected to high cycle fatigue loading is investigated by numerical simulations and cyclic MMB experiments. Similar to the quasi-static case, the numerical model includes lamina and interface elements. The description of the cyclic delamination crack growth rate is based on the cyclic degradation of bilinear interface elements, with subsequent unloading/ reloading cycles. In other words, the interfacial fatigue damage evolution law, added to the previously implemented user element routine, is a cohesive law that links fracture and damage mechanics to establish the evolution of the damage variable in terms of the cyclic crack growth rate. The constitutive cyclic damage model is calibrated by means of mixed mode fatigue experiments and reproduces the experimental results successfully and with minor error (Fig.2).

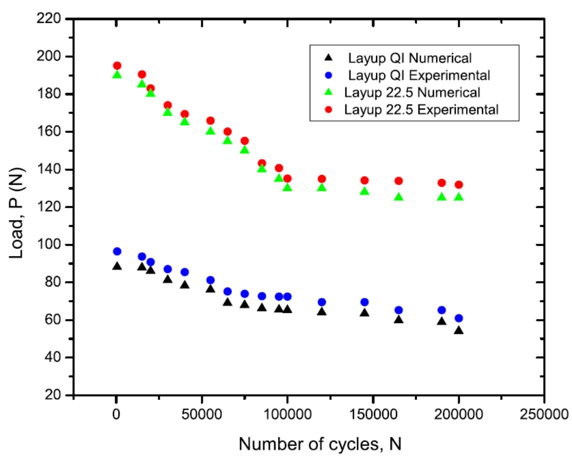

Fig.2: Load reduction with successive cycles with a mode mixity of 50% – comparison of numerical and experimental results after implementing the cyclic damage law in the numerical model

4 Conclusion

Overall, this work provides a numerical tool for simulating the delamination behavior of CFRP materials with various multidirectional stacking architectures, under mixed mode loading for any arbitrary mode mixity, and for quasi-static as well as cyclic loading. For the chosen multidirectional layups subjected to 50% cyclic mixed mode loading, the numerical model predicts the degradation of the applied load within successive cycles successfully when compared with the corresponding experiments. Under cyclic loading, the constitutive behaviour of the interface elements has been further extended by adding a fatigue damage variable and the numerical model predicts the degradation of the applied load within successive cycles successfully when compared with the corresponding experiments. The models have been validated by means of mixed mode bending experiments on CF/PEEK laminates, and they can be used for any CFRP-material provided that the required minimum experimental data set is available.

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