LOW VELOCITY IMPACT ON LAMINATE COMPOSITE WITH THERMOPLASTIC RESIN

C. Bouvet[1], P. García Pérez[2*], F. Dau[2] and P. Peres[3]

[1]Université de Toulouse; ICA (Institut Clément Ader)
ISAE (Institut Supérieur de l'Aéronautique et de l'Espace), 31055 Toulouse Cedex, FRANCE
Email: christophe.bouvet@isae.fr

[2] I2M (Institut de Mécanique et d'Ingénierie)
ENSAM (École Nationale Supérieure d'Arts et Métiers), 33405 Talence Cedex, FRANCE
Email: pablo.garcia-perez@ensam.eu, frederic.dau@ensam.eu

[3] Airbus Defence and Space, Établissement d'Aquitaine
BP 20011, 33165 Saint-Médard-en-Jalles Cedex, FRANCE
Email: patrick.peres@astrium.eads.net

ABSTRACT

Composite materials have been increasingly used in airframe and space applications because of their advantageous mechanical properties. Nevertheless, during the structure's life, damage induced by low velocity impact, such as matrix cracks, fiber breakage and delamination can drastically decrease the residual mechanical characteristics of the structure. There is a strong current trend towards a greater use of high-performance thermoplastics in composites structures for damage tolerance reasons. In this study, unidirectionnal carbon/PEEK laminate has been subjected to impact and the damage has been studied using C-scan investigations. The experimental results show higher delaminated area than expected. The damage morphology presents high delaminated interfaces situated at mid-thickness of the plate. These delaminations have also the characteristic to be asymmetric whereas the bounday conditions are symmetric. Afterwards, this paper shows that a "discrete ply model" is able to simulate the complex three-dimensional damage patterns in composite laminates with PEEK resin subjected to low velocity impact. Nevertheless, it is necessary to use low rate on the mode II interlaminar fracture toughness to recover the experimental results. The objective is together to simulate the impact damage and to better understand the unclassical damage morphology observed during impact with thermoplastic material.

1 INTRODUCTION

Nowadays the use of composite materials is fastly growing in potential applications in aerospace and automotive industries. Nevertheless, impact damage in composite structures may lead to significant reduction in structure compressive strength and this damage may remain unnoticed below the Barely Visible Impact Damage threshold. Damage in composite materials and structures involves multiple failure modes such as fibre breakage, fibre pullout, delamination between plies, matrix cracking, fibre-matrix debonding, etc.

Many computational methods and experimental characterization techniques are developed in the impact prediction of composite materials to measure the impact resistance and thereby to explain the failure criteria. Impact damage behaviors are very difficult to predict because they depend on many parameters. IM7/PEEK is a carbone fibre reinforced thermoplastic composite unidirectional laminate. It presents inherently nonlinear material properties with greater residual strength after impact, higher toughness, better delamination resistance and can absorb a greater quantity of energy in an impact and crash than using carbone fibre reinforced thermosetting composite.

In the current paper, a 3D damage and failure model of composite laminates subjected to low-velocity impact damage is described. The modelling of impact damage and its validation for IM7/PEEK laminate composite plate are presented.

2 IMPACT DAMAGE MODEL

To capture the effects of progressive damage and failure on laminated composite structures, failure modes in both the fibre and matrix resin must be considered. The model presented here considers fibre failure in tension and compression, matrix cracking taking into account permanent indentation and delamination. It is based on the use of cohesive zone models to capture delamination between plies of different orientation and transverse matrix cracking in cross-ply. The model is developed and implemented into Explicit/Dynamic Abaqus code with a VUMAT subroutine. The damage and failure model of composite laminates subjected to low-velocity impact is now presented.

A damage criterion for the fibre failure is derived from the energy balance based on crack band theory to dissipate a constant energy release rate per unit area in the 3D continuum element [1]. This energy-based criterion defines a stiffness degradation model that is introduced both in tension and compression. The linear relationships between stresses and strains in the volumic element represents the evolution of the damage in the fibre [2].

The fibre compressive failure behavior is more complicated than in tension. Crack initiation in compression is due to kink band followed by the crushing of fibres packages. Therefore, a compressive mean crushing stress is applied as a plateau to complete the law. Moreover, during the plateau, plasticity is also taken into account to prevent compressive strain from returning to zero to unloaded state [3].

Matrix cracking refers to the onset of damage at a material point which is based on Hashin's theory. The Hashin criteria is calculated in the neighboring volume elements of the zero-thickness cohesive element. This criterion is assessed at each time increment: the interface stiffness between two volume elements becomes zero if the criterion is reached and otherwise, it remains intact.

Permanent indentation is an important prognostic indicator of occurred impact. It reflects a non-closure of crack which is the result of the formation of debris inside matrix cracking. In this model, a pseudo-plasticity law has been used in order to predict the permanent indentation. It is experimentally observed that the permanent indendation remains approximately 30 % of maximum crack opening in both transversal and out-of-plane directions [4].

A failure mode which is widely observed in laminate composites is delamination between adjacent layers or plies of different orientation. This mode is commonly modeled with a cohesive interface elements based on fracture mechanics. Zero-thickness 3D cohesive elements are used to joint lower and upper ply volume elements. A failure criterion of interface element under mixed mode condition is introduced in the model. An exponential softening law is chosen to avoid the shock of the final fracture by introducing a complex state variable to track the extent of damage accumulated at the interface.

3 EXPERIMENT AND SIMULATION

In order to validate the impact damage model described above, an experimental low-velocity impact test was carried out. Postmortem evaluation of the damage delamination is performed through C-scan inspection and visual inspection of the permanent indentation.

Impact test was performed using a drop tower system with a $2{,}028\,\mathrm{kg}$ mass and $16\,\mathrm{mm}$ spherical impactor. Composite laminate plates of $150\mathrm{x}100\,\mathrm{mm}^2$ with $4{,}4\,\mathrm{mm}$ thick were made from carbon fiber/PEEK resin prepreg using an unidirectional symmetrical stacking sequence $[0_2/45_2/90_2/{-45_2}]_{2S}$. The detailed material properties of the composite plate are summarized in Table 1.

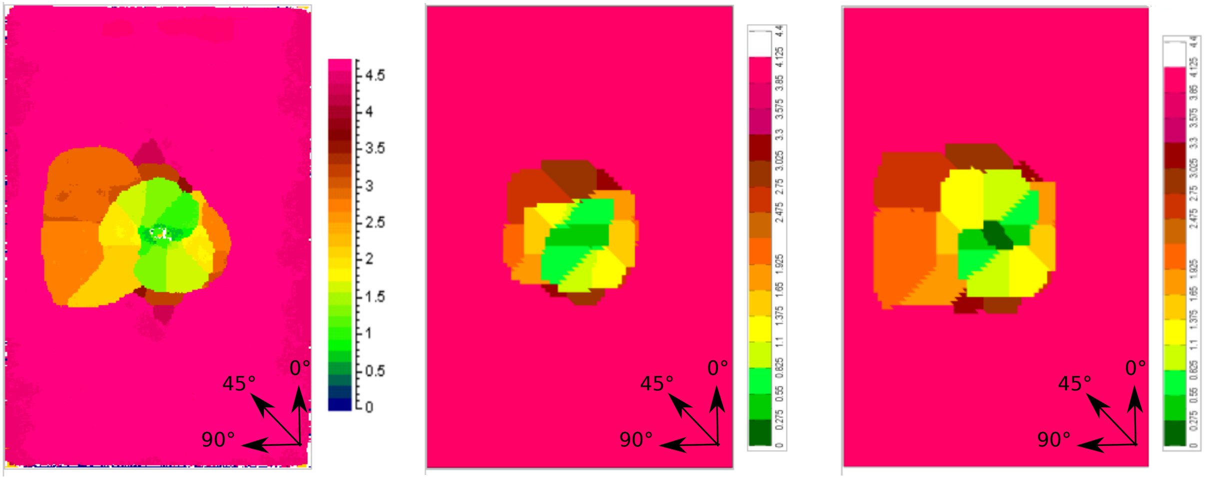
E_l^t (GPa)	Tensile Young's modulus in fibre direction	150
E_l^c (GPa)	Compressive Young's modulus in fibre direction	140
E_t (GPa)	Transverse Young's modulus	9
G_{lt} (GPa)	Shear modulus	5
S_{nt} (MPa)	Transverse failure stress	60
S_{tt} (MPa)	Shear failure stress	160
X_{crush} (MPa)	Longitudinal compressive mean crushing stress	250
ν_{lt}	Poisson's ratio	0.3
ε_0^t	Tensile strain in fibre direction at damage initiation	0.0167
ε_0^c	Compressive strain in fibre direction at damage initiation	-0.0096
G_I^t ($\mathrm{N\,mm^{-1}}$)	Fracture toughness for mode I in traction	80
G_I^c ($\mathrm{N\,mm^{-1}}$)	Fracture toughness for mode I in compression	40
G_I^d ($\mathrm{N\,mm^{-1}}$)	Interface fracture toughness for opening mode (I)	$0.5 \rightarrow 1$
G_{II}^d ($\mathrm{N\,mm^{-1}}$)	Interface fracture toughness for shear mode (II and III)	$2 \rightarrow 0.4$

Table 1. Material properties of carbon fiber/PEEK laminate for numerical simulations

Firstly, a numerical simulation of $20\,\mathrm{J}$ impact was performed with $G_I^d = 1\,\mathrm{N\,mm^{-1}}$ and $G_{II}^d = 2\,\mathrm{N\,mm^{-1}}$ but the results are not accurate with respect to the experiment. A second simulation was performed with interface fracture toughness values of $G_I^d = 0{,}5\,\mathrm{N\,mm^{-1}}$ and $G_{II}^d = 1\,\mathrm{N\,mm^{-1}}$. Figure 1 shows the comparison of the delaminated areas through the thickness obtained from the experimental test (a) and impact damage model (b). The model under-predicts the delaminated areas.

It has been reported the effects of shear displacement rate on the mode II interlaminar fracture toughness in graphite/PEEK laminates [5]. It is shown that the PEEK material exhibits ductile crack growth at low rates and brittle crack growth at high rates. The change on fracture mechanism resulted in a decrease from $1{,}9$ to $0{,}4\,\mathrm{N\,mm^{-1}}$.

Keeping G_I^d to $1\,\mathrm{N\,mm^{-1}}$ and decreasing G_{II}^d to $0{,}4\,\mathrm{N\,mm^{-1}}$ as explained, the shape and distribution of delaminated areas are in better agreement between experimental and numerical results, as shown in Figure 1 (a) et (c). The difference between numerical results is mostly associated with the energy required to propagate the delamination in mode II. The model is able to predict the asymmetrical area and principal orientations of the delamination without introducing the asymmetric damage mode in the constitutive equations.



(a) (b) (c)

Figure 1: C-scan delamination area from impacted side: (a) experiment (b) simulation with $G_{II}^d = 1\,\mathrm{N\,mm^{-1}}$ et (c) simulation with $G_{II}^d = 0{,}4\,\mathrm{N\,mm^{-1}}$

4 CONCLUSION

The capability of a cohesive-based impact damage model is investigated to predict more complex three-dimensional damage patterns induced by impact. The numerical simulations were validated against experimental results.The proposed formulation has shown a good ability to predict the low-velocity impact behavior of IM7/PEEK composite laminates. The results reported in [5] are verified through two simulations with different constant values of G_{II}^d. In order to capture the main differences between the predictions and experiments, the observed Ultrasonic C-Scan delamination size and shape at interfaces are reported and discussed. Further investigations are needed to clarify the main reasons of the discrepancies.

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