INTEGRATED NUMERICAL ANALYSIS FOR COMPOSITE DAMAGE TOLERANCE

Guinard Stéphane, Thévenet Pascal, Vinet Alain, Maison-Le Poëc Serge
EADS-CCR

Keywords: *impact, damage tolerance, laminated composites*

Abstract

From initial damage to ultimate failure, there is a range of loads that structures can undergo while still keeping within the safety requirements. Mastering this damage tolerance would enable to operate an aircraft with damaged structures, providing the remaining capabilities could be certified. When compared with metals, composite materials improve the structural damage tolerance, since their constitutive heterogeneity enforces damage to distribute over lengths wider than in homogeneous media. Characterizing composite damage tolerance asks for expensive and time consuming experimental campaigns. In order to integrate damage tolerance in the design and the maintenance in a cost-effective way, numerical tools should enable the calculation of damage initiation and propagation: a thorough mastering of the modeling, the computation, and the experimental characterization of damage evolution has to be achieved. This paper summarizes the EADS's global approach to hit this target.

1 Introduction

Aeronautical design and maintenance engineers are faced to pragmatic situations when dealing with damage tolerance:

• When designing an aircraft, from cosmetic to structural elements, one has to assess the integrity of structures that will be subjected to damage events. Models should characterize the structural properties from the initial state to the damage initiation, propagation, and ultimate failure.

• When operating an aircraft, one has to decide either to repair or replace in-service damaged parts. Models should characterize the structural properties from measured damage sizing to propagation and rupture.

Low velocity impacts on laminated composites are of primary interest when dealing with damage tolerance, since both situations are encountered. The lecture will focus on preliminary tools CRC is developing, aiming at an integrated numerical analysis of damage tolerance.

2 Characterization of the induced damage

2.1 US C-Scan

The numerous low-velocity impact-testing campaigns conducted at EADS-CCR resulted in a thorough understanding of the elementary damage events occurring in the laminate [1]. A cinematic scheme was built on the basis of ultrasonic scanning and distance-magnitude analysis.

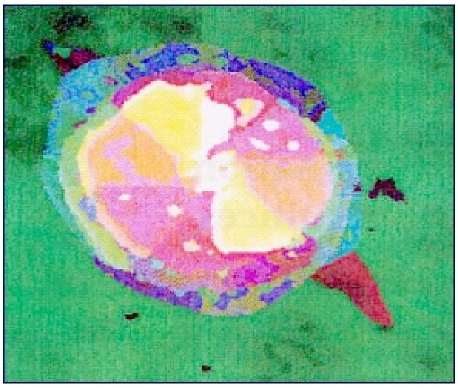

Fig. 1 - US C-Scan of a $(45°_2,0°_2,-45°_2,90°_2)_S$, 7.1 J impacted T300/914 laminate

During the loading, transverse cracks develop along the fibres in each UD ply, with symmetry with the central contact area. A released strip in each ply is free of moving in the third direction, normally to the mid-plane (Fig. 2). If depicted from the interfacial plane between two of these damaged plies, the released planes are to be considered as:

- an interfacial traction area, above the bottom released strip;
- an interfacial compression area, under the top released strip.

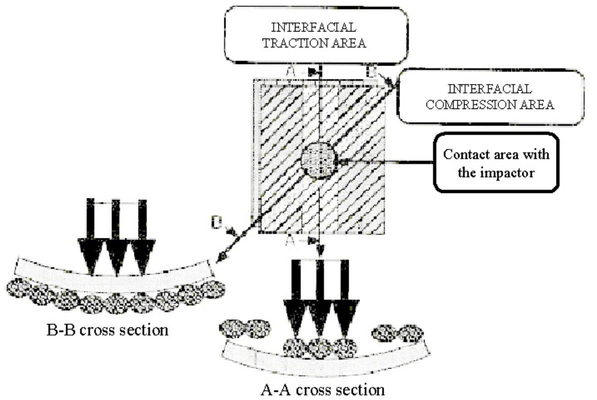

Fig. 2 - cinematic scheme extracted from [1]

Delamination develops in the traction area, with the compression area acting as an anti-delaminating agent (Fig. 2). Pairs of twin-triangles develop at each interface [2]. With the regular rotation of fibres from one ply to the other in quasi-isotropic laminates commonly used in aeronautical structures, this scheme depict a typical “double-helix” when repeated through all the thickness. Increasing from the impacted side to the free side of the impacted plate, delaminations are wrapped in a conical shaped envelope. This conical shape makes it possible to visualise the whole periphery of the double helix through ultrasonic scanning.

2.2 In-service inspections

During service life, aircraft are regularly inspected to detect any defect on the composite structures. In-situ investigation means are far less sophisticated than US C-Scan performed in laboratory conditions. Nevertheless, a prospective scheme is to operate these portable investigation means to characterize the outer-skin damage induced geometry. In a long-term, when effective calculation models will be operational, an optimization computation would help getting the actual delaminated configuration associated to this external damage induced geometry. Then classical fracture mechanics would give the residual load-carrying capabilities (cf. § 4).

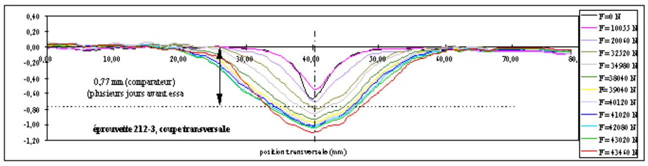

Fig. 3 - measured impact external induced damaged area on a sandwich panel

3 Calculation of the impact induced damage

3.1 Empiric model

Before exploring sophisticated FE models, pragmatic analytical models have been developped in order to reduce experimental campaigns. Empiric laws were extracted from these campaigns. Two parameters were considered, the indentation depth and the total delaminated area. The results of existing tests permitted to obtain master curves of these parameters [3]. This model was implemented in a software, LAMKIT©.

3.2 FE damage model

Experimental evidence was given to the equivalence between low-velocity impacts and quasi-static indentation loading for the same incident energy. For an impact, the quasi-static iso-energy is considered, which enables a time-independent numerical treatment. A modified Hertz distribution under the impactor is considered [4], [5], [6].

Damage meso-models designed at LMT (Fig. 4) [7] were dedicated to plane-stress loading at first. Though some specifies with regards to plane-stresses loading have been raised up, experimental observations showed that the elementary damage events are the same as those considered in original LMT damage meso-models: fibre rupture, fibre-matrix debonding, transverse cracks and delamination. Specifies are inherent to a strong coupling between these elementary events, related to highly localised stress transfers, especially out-of-plane stress transfers: delaminations seem to be controlled by the neighbouring transverse cracks.

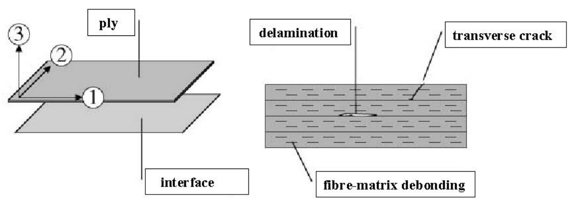

Fig. 4 – damage mesomodel -

At the mesoscopic scale, a laminate is considered as a stacking of homogenised plies and interfaces. In opposition to macro- and micro-scale studies, meso-scale enables a balance between numerical weight and physical reliability. Fibre-matrix debonding and transverse cracks will be described through their effects on the elastic moduli of the plies, delaminations through their effects on the elastic moduli of the interfaces.

Ply modelling

Strain energy:

The damage effects of out-of-plane stresses are integrated in the original model. The expression of the strain energy is updated. Though new stresses are introduced, the same internal variables, d_{ps} and d_{pt} are used to represent respectively fibre-matrix debonding and transverse cracks effects on elastic moduli G_{12}, G_{13} and E_2. Energies are split into their compressive and tensile parts (respectively non-active and active with regards to damage growth). A γ coefficient is associated to the non-linear compressive behaviour in the fibre direction. At least, the strain energy E_D is written as follows:

$$E_D = \frac{1}{2}\left\{\begin{array}{c} \dfrac{\langle\sigma_{11}\rangle_+^2}{E_1^0(1-d_f)} + \dfrac{\gamma\langle\sigma_{11}\rangle_-^2}{E_1^0} + \dfrac{\langle\sigma_{22}\rangle_+^2}{E_2^0(1-d_{pt})} + \dfrac{\langle\sigma_{22}\rangle_-^2}{E_2^0} + \dfrac{\sigma_{33}^2}{E_3^0} \\ + \dfrac{\sigma_{12}^2}{G_{12}^0(1-d_{ps})} + \dfrac{\sigma_{13}^2}{G_{13}^0(1-d_{ps})} + \dfrac{\sigma_{23}^2}{G_{23}^0} \\ - \dfrac{2\nu_{12}^0\sigma_{11}\sigma_{22}}{E_1^0} - \dfrac{2\nu_{23}^0\sigma_{22}\sigma_{33}}{E_2^0} - \dfrac{2\nu_{13}^0\sigma_{11}\sigma_{33}}{E_3^0} \end{array}\right\}$$

Damage forces:

Conjugated thermodynamic forces Y_{dps} and Y_{dpt}, related to damage variables d_{ps} and d_{pt} respectively, are expressed by deriving the strain energy with respect to d_{ps} and d_{pt}:

$$Y_{dps} = \left.\frac{\partial E_D}{\partial d_{ps}}\right|_{d_{pt}} = \frac{<<\sigma_{12}>>^2}{2G_{12}^0(1-d_{ps})^2} + \frac{<<\sigma_{13}>>^2}{2G_{13}^0(1-d_{ps})^2}$$

$$Y_{dpt} = \left.\frac{\partial E_D}{\partial d_{pt}}\right|_{d_{ps}} = \frac{<<\langle\sigma_{22}\rangle_+>>^2}{2E_2^0(1-d_{pt})^2}$$

Coupling between damage modes:

To depict the interactions between transverse cracks and fibre-matrix debonding, two coefficients b_{ps} and b_{pt} are introduced. Two new damage forces are expressed as follows:

$$d_{ps} = \frac{\sqrt{Y_{ps}} - \sqrt{Y_{ps}^0}}{\sqrt{Y_{ps}^c}} \text{ if } \begin{cases} d_{ps} < 1 \\ d_{pt} < 1 \end{cases}, \text{else } d_{ps} = 1$$

$$d_{pt} = \frac{\sqrt{Y_{pt}} - \sqrt{Y_{pt}^0}}{\sqrt{Y_{pt}^c}} \text{ if } \begin{cases} d_{ps} < 1 \\ d_{pt} < 1 \\ Y_{pt} < Y_{pt}^f \end{cases}, \text{else } d_{pt} = 1$$

Damage evolution laws:

damage initiation thresholds Y^0, critical damage thresholds Y^c and a brittle threshold y^f are introduced in a simple damage evolution law:

$$Y_{ps} = Sup|_t \{Y_{dps} + b_{ps} Y_{dpt}\}$$
$$Y_{pt} = Sup|_t \{Y_{dpt} + b_{pt} Y_{dps}\}$$

Experimental identification

Though out-of-plane damage activity was introduced in the model, no new material constant is needed. Experimental identification procedure used for the original model [8] is therefore still useful for the modified model. The strategy relies on tests conducted on specimens with characteristic layouts, which activate only the damage mode to be identified. The material used in this study has already been identified through this procedure at LMT [8].

Numerical implementation

A software with the original model integrated has been developed at LMT for the analysis of in-plane stresses problems like laminated plates with a hole under in-plane tension: DSDM (Delamination Simulation by Damage Mechanics) [9]. The numerical strategy proceeds in two steps: a first 2D elastic computation is performed on the whole structure with standard finite element software (Fig. 5). Then the displacements along a central circular line surrounding the impact area are extracted from the elastic solution. The 3D non-linear analysis is performed inside this line with DSDM. A fast Fourier Transform enables to treat the 3D non-linear problem on the volume as series of 2D non-linear problems on orthoradial planes.

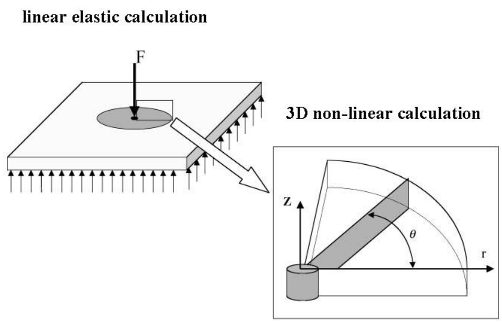

Fig. 5 - numerical strategy in DSDM

Each 2D non-linear problem is solved with a Large TIme Increment Method (LATIN Method) [10]. Calculation results show good correlation with experimental observations.

Intralaminar damage results

Damaged areas in the plies are to be compared with the released strips in the plies: according to the cinematic scheme, the delamination configuration would result from these released strips. These strips and their orientations are simulated (Fig. 6); the size of the strips is increasing from the impacted side to the free side of the plate, as expected when analysing experimental results. The fundamentals of the “double-helix” shape are simulated. The size of the bottom basis of the damaged area was compared to the measured maximal width of ultrasonic C-Scan: good correlation was found with experimental results.

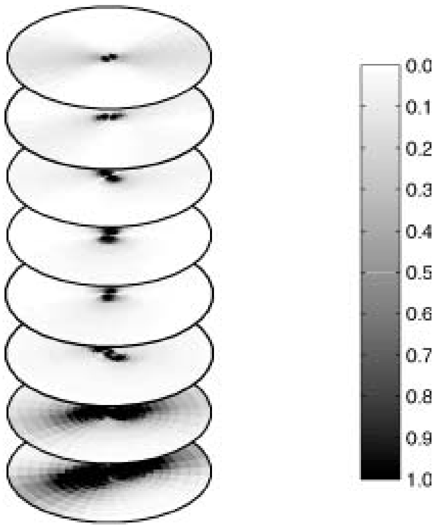

Fig. 6 - damage calculation results in the plies

Interfacial damage results

In the cinematic scheme proposed for explaining the double helix, intralaminar damage is the precursor of delamination. Therefore, a phenomenological interfacial model was built on this cinematic scheme to validate interlaminar damage results and the cinematic scheme: this scheme is a proposal for interpreting couplings between intra- and interlaminar damage. In this model, interfacial damage is directly connected to the damage in the neighbouring plies:

$$d_i = \mathrm{Sup}\left\{d_{ps}^- - d_{ps}^+ ; d_{pt}^- - d_{pt}^+\right\}$$

where d_i is the interfacial damage at an interfacial M Gauss point, X_+ and X_- are intralaminar quantities at the associated M_+ and M_- Gauss points in the plies above and under the interface under consideration. Results show a good correlation with the observed double helix, which validate both the intralaminar results and the cinematic scheme (Fig. 7).

Remaining difficulties

This phenomenological model breaks with classical interfacial model used at LMT [9]. These "classical" models were also tested but failed into catching the coupling between intra- and interlaminar damage. This coupling has an intrinsic discrete nature: intralaminar cracks concentrate stresses at their tips and promote interfacial damage. The numerical tests performed showed that such a discrete phenomenon could not be catched by a discrete model.

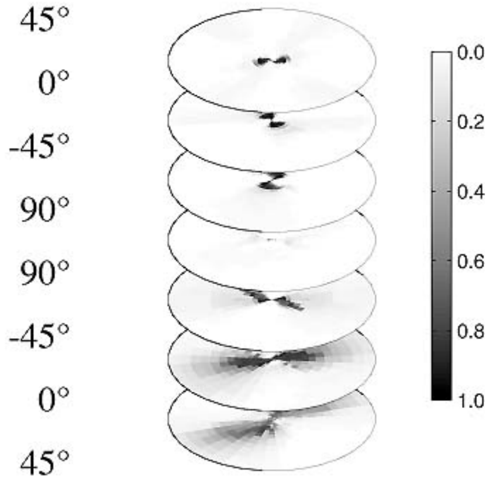

Fig. 7 - damage calculation results at interfaces

In the framework of a DGA (French MoD) granted project, two studies were initiated recently, emphasizing this discrete aspect. Exploratory works have already been published [11].

Regarding the numerical implementation in industrialized softwares, EADS-CCR already tried to export this kind of models from university mockups to actual design office software. Classical algorithms revealed difficulties for integrating high material non linearities.

4 Calculation of delamination propagation

Since the initial post-impact damaged configuration was calculated from the impact parameters, the next calculation aims at simulating the propagation of the impact induced delaminations. Classical fracture mechanics models are used [12].

These calculations are still performed with a "hand-made" meshing of the delaminated geometry. The numeric link between the initiation calculation, performed with a FE damage model, and the propagation calculation, performed with a fracture mechanics model, is still not established. The feasibility of the full integrated calculation will be demonstrated within a GARTEUR action group (AG28: "impact damage and repair of composite structures").

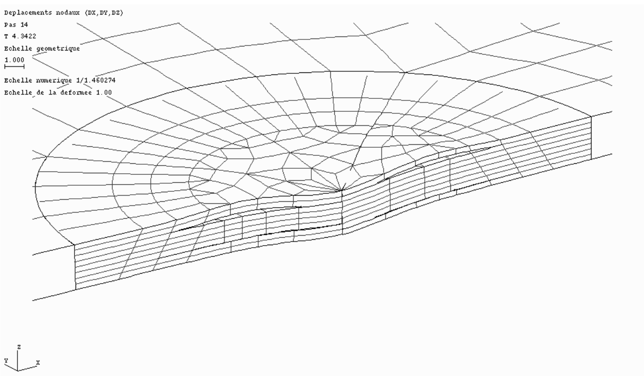

Fig. 8 - propagating delamination under in-plane compression of the laminate

5 Conclusion

There still remains great efforts before performing fully software-integrated damage tolerant designs for composite structures. But through both experimental and numerical progresses, some first steps towards this ultimate goal were built. Remaining difficulties have been identified and keep under research exploration.

References

[1] Guédra-Degeorges D., Maison-Le Poëc S., Renault M., Numerical simulation of the behaviour after impact of a carbon epoxy laminated plate, ICCM8, 1991.

[2] Clark G., Modelling of impact damage in composite laminates, Composites, 20(3), pp. 209-214, 1989.

[3] Vinet A., Guédra-Degeorges D., établissement de courbes maîtresses pour la prévision des dommages d'impact sur CMO, Comptes rendus des JNC12, pp. 717-182, 2000.

[4] Greszuk B., Damage in composite materials due to low velocity impact. In Zukas and al. editors, Impact Dynamics, pp.55-95, John Wiley and Sons.

[5] Tan T. and Sun C., Use of statical indentation laws in the impact analysis of laminated composite plates. Transactions of the ASME, 52, pp. 6-12, 1985.

[6] Guédra-Degeorges D., Maison-Le Poëc S., Trallero D., Petitniot J.L., Analyse et simulation des mécanismes de dégradation d'une plaque composite impactée, CNCS, Giens, 1993.

[7] Ladevèze P., Sur la mécanique de l'endommagement des composites. In Bathias c. and Menkès D. editors, Comptes-rendus des JNC5, pp. 667-683, Paris, Pluralis, 1986.

[8] Ladevèze P. and Le Dantec E., Damage modelling of the elementary ply for laminated composites. Composite Science and Technology, 43(3), pp. 257-267, 1985.

[9] Allix O., Damage analysis of delamination around a hole. In Zienkiewicz O., editor, New Advances in Computational Mechanics, pp. 411-421, Elsevier Science, 1992.

[10] Ladevèze P., Sur une famille d'algorithmes en mécanique des structures. Comptes-rendus de l'Académie des Sciences, 1985.

[11] Ladevèze P., Lubineau G., An enhanced model on the micro- and mesoscale for laminated composites, Mechanics of materials, Elsevier, to be published.

[12] Thévenet P., Impact sur matériau composite monolithique – modélisation et simulation par éléments finis de la compression après impact -, rapport EADS-CCR, 2000.