NUMERICAL APPROACH TO DESIGN AERONAUTICAL COMPOSITE LAMINATE BASED ON IMPACT DAMAGE TOLERANCE PHILOSOPHY

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Abstract

Composites are known to be vulnerable to out-of-plane solicitation such as impact. Investigating laminate's residual properties in function of the damage detection is the main purpose of design by impact damage tolerance. Because an experimental campaign is long and costly, a numerical approach would lead to a time gain and stays a really good alternative. The model developed in Institut Clément Ader over these last 10 years enables to expose behaviour of composite laminate plates subjected to low velocity/low energy impact and compression after impact (CAI). Damages such as permanent indentation, fiber failures, matrix cracks and delamination are taken into consideration at each step thanks to a discrete ply modelling. The originality of this work stands on the possibility to conduct a numerical campaign and globally show off the stacking sequence effects on the impact damage tolerance of the structure and so on designing composite structures. Here is the first step of this numerical approach.

1. Introduction

Composites are more and more used in structures of many fields for their high strength-to-weight ratio. But because of their vulnerability, they are too often over-designed. Low velocity impacts can occur during manufacturing or operation on composite structures and can lead to a significant reduction of the residual properties without visibly marking the surface (this damage is called permanent indentation). In aeronautics, the design is based on the visibility of the damage (Fig. 1): under a certain level of detectability the structure should withstand extreme loads; beyond this level the impacted structure should withstand limit loads without sudden failure until the detection of the damage during inspection. This level of detection is called "Barely Visible Impact Damage", or BVID [1], and is linked to the geometry and properties of the structure and to the impact energy.

From understanding to predictive work, many studies have been run on damages induced by low-velocity impact since 90's [2-5]. Important researches have been done on capturing and modeling delamination with good results [6-10] and on investigating stacking sequence effects [11, 12]. Following the impact, in order to estimate the residual strength and judge the damage tolerance of the laminate, interest is finally focused on modeling compression after impact with for instance some quite accurate models developed by Gonzalez et al. [13] and recently published by Tan, Falzon et al. [14]. Finally, related to the impact damage tolerance designing philosophy, important signification is given to indentation permanent as a predictive mark to evaluate the residual capabilities of the structure [15].

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This phenomenon is not well controlled yet, because it depends on several parameters: plate geometry, material, stacking sequence, impact energy or impactor shape… Some formulations exist to involve dent during impact test simulations: “plastic-like” model included in the matrix behaviour [16], using anisotropic elasto-plasticity theory [17], non-linear shear of the intralaminar damage model [8, 14]…

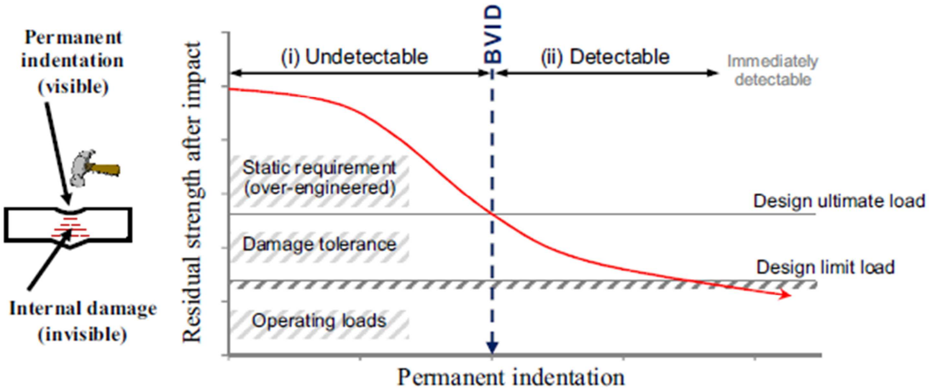

Figure 1. Damage tolerance concept with detectable and undetectable damages.

The Discrete Ply Model developed at the Institut Clément Ader by Bouvet et al. enables us to capture damages such as permanent indentation, delamination, fiber failures and matrix cracks for each step from the impact to the residual strength [16, 18, 19]. This model was validated by a test/simulation correlation from different basic sequences in terms of delamination areas, force-displacement curves and force-time curves [18]. It also shows quite accurate results with dent depth and residual strength prediction [16, 19], taking into account a certain experimental dispersion.

The design approach is ideally to give the residual strength of a laminate for a given detectable damage near to the BVID (Fig.2). Firstly, for a given impact energy on several stacking sequences, interest is focused on impact damages, permanent indentation and residual strength. The aim of this work is to run a numerical campaign and to study the effect of the laminate stacking sequence on the impact damage tolerance of the structure. Secondly, after getting the impact energy associated with (or close to) the BVID, residual strength of interesting laminate stacking sequences at the BVID can be studied. Only the first step is exposed here, enabling one to link impact damage visibility and residual strength.

2. Numerical modeling

2.1. Element formulation and behavior law

The model of composite damage used in this study, named “Discrete Ply Model” (DPM) was extensively presented in [16, 18, 19]. Only a brief recall is done in order to better understand the CAEI model and the interested reader can find more details in [18]. The principle is to simulate the major failure modes observed in composite impact tests (delamination, matrix cracking and fiber failure) as follows (fig. 3):

- The delamination is simulated with classical interface elements between two consecutive plies; each ply being modeled with one volume finite element in the thickness. Then the damage in the delamination interface elements is classically driven using fracture mechanics. One more consideration is a communication with the volume element and the local effect that fiber failures could have on close interfaces.

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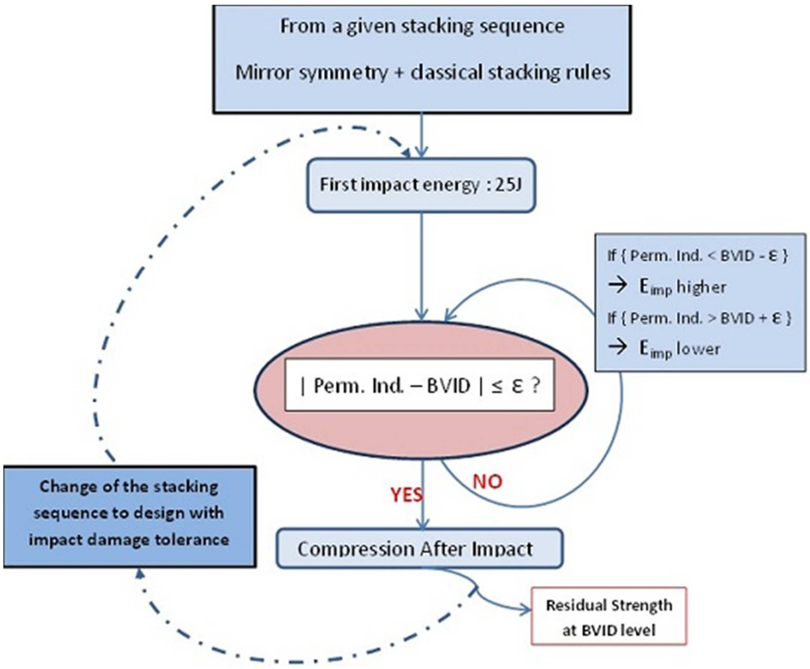

Figure 2. Ideal numerical approach on several laminate sequences and study of the residual strength at given energy and at BVID level damages.

- The intra-ply matrix cracking is simulated using interface elements normal to the transverse direction. The damage in the matrix cracking interface elements is driven using Hashin's Criterion calculated in neighboring volume elements (Eq. 1):

$$\left(\frac{\sigma_t^+}{\sigma_t^f}\right)^2 + \frac{\tau_{lt}^2 + \tau_{tz}^2}{(\tau_{lt}^f)^2} \leq 1 \qquad (1)$$

With (l,t,z) the orthotropic directions, σ_t^f the transverse failure stress and τ_{lt}^f the shear failure stress. A second part of the law is based on the same formulation that for delamination criteria. Even if matrix crack is not detrimental for residual strength, delamination is usually linked to it [21, 22]. These interface elements constrain to a complex mesh, but permit to naturally obtain the coupling between intra- and inter-laminar damage. This coupling is known as crucial to simulate the complex damage morphology developing in composite structures during impact.

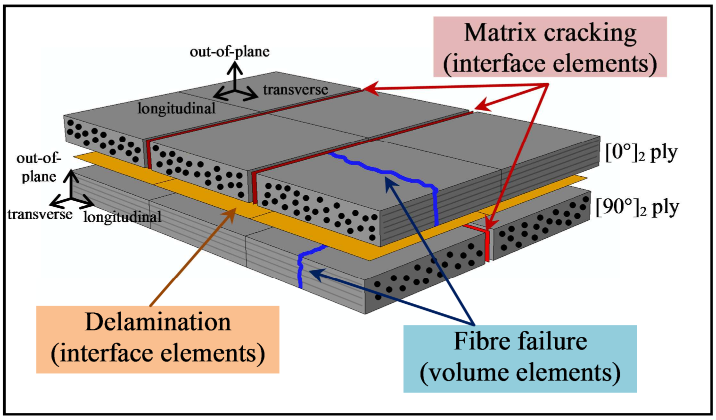

Figure 3. Modeling of composite damages with the different element types in each oriented ply

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- Fiber failure is taken into account using conventional continuum damage mechanics but with original formulation between the integration points of the element to produce a constant energy release rate per unit area (Eq. 2). This approach can be compared to methods based on characteristic element length which makes possible mesh-size independent modeling.

$$\int_V \left(\int_0^{\boldsymbol{\varepsilon}^1} \boldsymbol{\sigma_l d\varepsilon_l} \right) . \boldsymbol{dV} = \boldsymbol{S.G_I^f} \tag{2}$$

Where $\boldsymbol{G_I^f}$ is the energy release rate in opening mode in fiber direction, *V* and *S* are element volume and section, $\boldsymbol{\sigma_l}$ and $\boldsymbol{\varepsilon_l}$ are longitudinal stress and strain, and $\boldsymbol{\varepsilon^1}$ is the strain of total degradation of fiber stiffness.

Once strain of damage initiation in traction $\boldsymbol{\varepsilon_t^0}$ or in compression $\boldsymbol{\varepsilon_c^0}$ is reached, a damage variable corresponding to a linear decrease of the stress is calculated and stresses are determined from the damaged orthotropic elastic stiffness matrix. In compression a plastic behavior is considered and a crushing stress $\boldsymbol{\sigma^{crush}}$ [20] is applied as a plateau.

2.2. Permanent Indentation Modeling

For the model validation, it was initially chosen to consider permanent indentation into matrix effect [16]. But because permanent indentation is all the higher as the fiber breakage is important, there is also the possibility to integrate it into fiber behaviour law.

Then permanent indentation is linked to shear-lz behaviour of the fiber. One does not have to neglect that matrix and debris could play a role likewise. It can be considered that fiber breakage is also associated with blocking debris and the formulation is just considered with fiber behaviour as it can be with matrix behaviour.

2.3. Material and boundary conditions

The model is so used to simulate an experimental impact test and a compression after impact test on a 4.16x100x150mm^3 rectangular laminate plate of T700/M21 UD carbon/epoxy composite. Properties used in the model are exposed in Table 1. The number of ply is fixed at 16 plies of 0.26-mm thickness, and orientations in the stacking sequence are limited to 0°, +/-45° and 90° with the same fiber percentage for each direction, to conserve membrane stiffness. Considering symmetrical reasons, only a half plate is meshed. The boundary conditions are given by the contact with a fixed rigid body, representing experimental condition tests exposed hereafter (Fig. 4).

For the impact test, the plate is supported by a 75x125mm^2 window and is impacted in its center by a 2-kg hemispherical impactor of 16-mm diameter, numerically assumed non-deformable. Boundary conditions of CAI are then set during relaxation steps of the plate. According to the AITM 1-0010 standards, they consist of two longitudinal stabilizing knives distanced by 90mm and two clamping blocks at the lower and upper sides of the plate.

Table 1. Material properties used in the model.

E_l^t (GPa)	E_l^c (GPa)	E_t (GPa)	ν_{lt}	G_{lt} (GPa)	G_{tz} (GPa)
130	100	7.7	0.3	4.75	2.9
σ_t^f(MPa)	τ_{lt}^f(MPa)	σ^{crush}(MPa)	ε_t^0	ε_c^0	
60	110	250	0.018	-0.0125	
$G_{I,c}^d$(N/mm)	$G_{II,c}^d$(N/mm)	G_t^f (N/mm)	G_c^f (N/mm)		
0.4	1.8	130	10		

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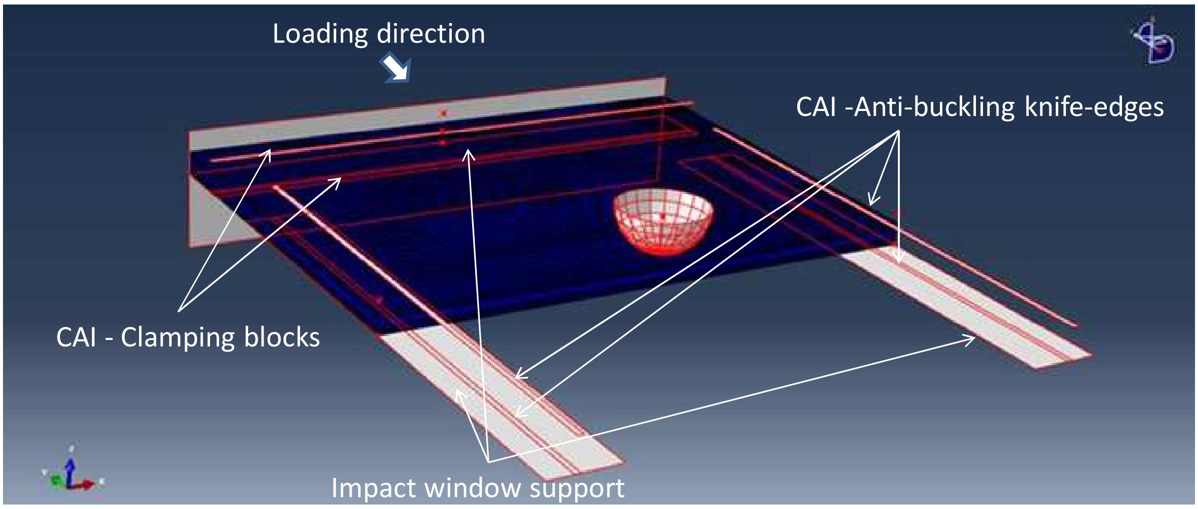


Figure 4. Impact and CAI boundary conditions of the DPM.

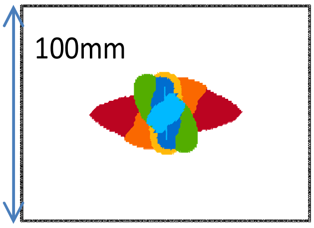
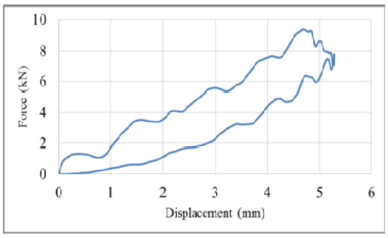
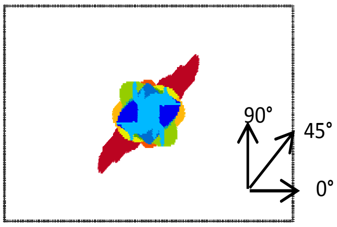
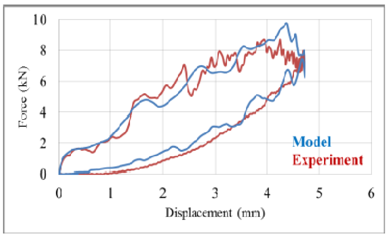
3. Numerical approach and first results

3.1. Configuration of the approach

The model validation tests [18-19] have been run on stacking sequences with double-plies based on a variation of the reference $[0_2/45_2/90_2/-45_2]_S$. This study was run out from this reference configuration, considering laminates more industrial with 0.25-mm thick plies. The classical rules of symmetry and external +/-45° plies are respected, and then all declensions are possible.

The first campaign consists in 25J impact and CAI tests on several laminates to point out effect of stacking sequence. The energy of 25J is chosen according to the standards ASTM D 7136/D 7136M specifying that impact energy is 6.7J/mm times the nominal thickness of the specimen. Impact curves, delamination areas, permanent indentation values and CAI strengths are then extracted from these tests. Some experimental tests enable to compare numerical results.

3.2. Some 25J impact tests results for varying layups

Stacking sequences and permanent indentations	Delamination areas	Impact Curves
Ref $[0_2/45_2/90_2/-45_2]_S$ 0.44mm		
A $[45/-45/90/0/90/0/45/-45]_S$ 0.40mm		

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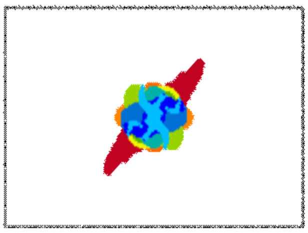
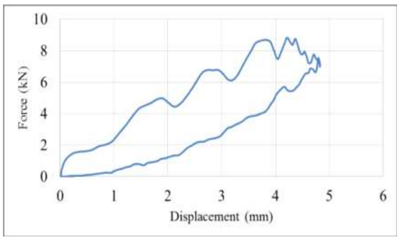
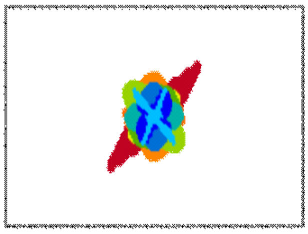
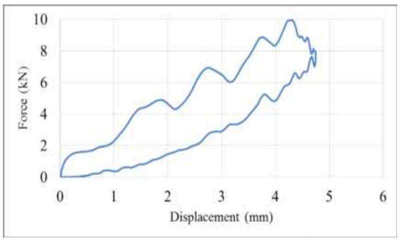
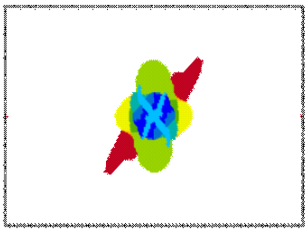
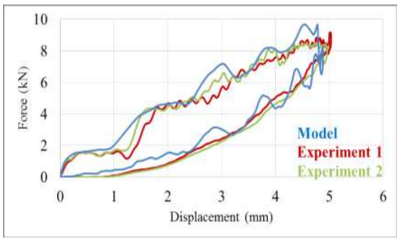
B $[45/-45/90/0_2/90/45/-45]_S$ 0.38mm		
D $[45/-45/0/90_2/0/45/-45]_S$ 0.33mm		
K $[45/-45/0/45/-45/0/90_2]_S$ 0.30mm		

Figure 5. Some impact results from simulation tests and some experimental curves for comparison.

Several stacking sequences were numerically tested; only 5 are presented in Figure 5. However delamination behaviour is more complex in certain other cases. Indeed in some case not exposed here, one could expect propagation in the last interface but the numerical result is more restrained. Other experimental tests would be performed to confirm or invalidate these results.

3.2.2 CAI strength and damage visibility

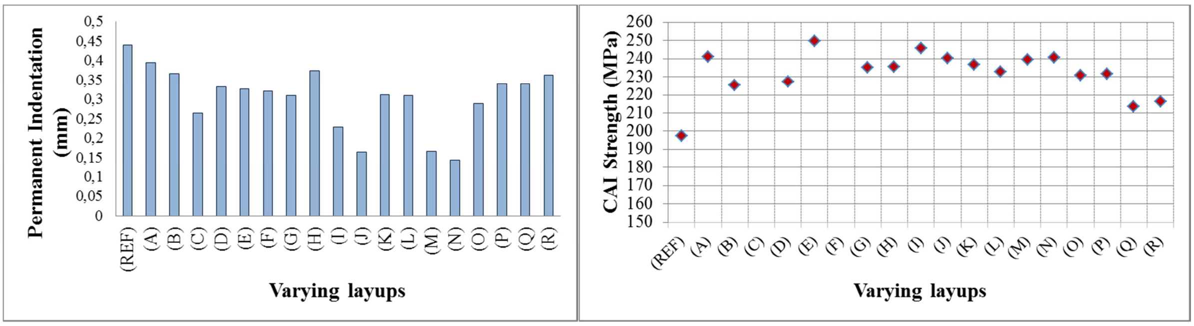


Figure 6. Permanent indentations and CAI strengths of several stacking sequences.

From this first approach, after obtaining impact behavior, the values of permanent indentation and CAI strength of each layup is extracted (Fig 6). These two parameters are crucial to design in accordance to damage tolerance philosophy. Seeing CAI strength, it can be pointed out that stacking sequence Ref is not interesting. Indeed, it confirms that doubling plies drives to a lower residual strength. However, the visibility is most important and gives this layup a compatibility with impact damage tolerance

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philosophy. Layups I and N do not give good damage visibility, and so are bad candidates in this design approach. The good compromise could be given by layup A, E or H (fig 7). This choice being dependent on importance given to each criterion.

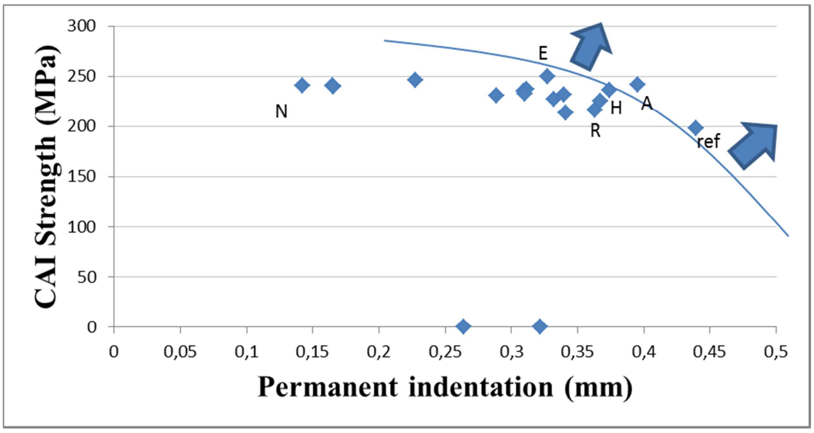

Figure 7. CAI strength in function of permanent indentation for each layup.

4. Conclusions

The model developed in Institut Clément Ader by Bouvet et al. can now be used to run a numerical campaign on several stacking sequences from impact to compression after impact. Here was presented a numerical 25J impact campaign followed by CAI test. More than getting information about impact behaviour, two key parameters such as permanent indentation and residual strength are globally well represented. This is capital in order to design laminate composite with higher residual strength possible for a suitable damage visibility.

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