ON THE INTRA/INTERLAMINAR COUPLING OF LAMINATED COMPOSITES

E. Abisset[1*], P. Ladevèze[1], F. Daghia[1]

[1]*LMT-Cachan, (ENS Cachan, CNRS-UMR8535, UPMC, PRES UniverSud Paris), 61, avenue du Président Wilson, 94230 Cachan, France*
**abisset@lmt.ens-cachan.fr*

Keywords: Damage mesomodel, Transverse cracking, Delamination, Coupling

Abstract

The prediction of damage and failure of laminated composites requires an accurate description of the elementary degradation mechanisms within the plies and the interfaces. Transverse ply cracks and interface delaminations may interact to generate complex failure scenarios. If a continuum, mesoscale model is considered for plies and interfaces, this interaction must be introduced within the constitutive modeling. In this paper, a new interface mesomodel including the effect of adjacent ply cracks on the stiffness and delamination behavior of the interface is proposed. Numerical simulations highlight the role of ply/interface interaction in the development of composite structures' damage and failure scenarios.

1 Introduction

An accurate prediction of the damage and failure behavior of composite structures requires a physically sound description of the degradation mechanisms occurring within these materials. Subcritical degradations, such as transverse intraply cracks and local delaminations, can interact across the laminate to produce complex failure scenarios, such as the ones observed in [1]. A complete discrete description of all the ply scale cracks being unfeasible for structural computations, mesoscale approaches, based on a continuum description of the composite plies and interfaces, are often introduced for the simulations. The interaction between ply cracks and delaminations must in this case be accounted for in the definition of the interface constitutive model.

The aim of this paper is to propose a new interface mesomodel accounting for the influence of the adjacent plies on the behavior of an interface [2]. This is a generalization of a previous, simplified version [3] to the case of different crack densities in the adjacent plies, a situation occurring quite often in industrial and academic test cases alike (some classical examples being quasi-isotropic and cross-ply laminates under tension).

The effect of the transverse ply cracks on the interface, as seen at the mesoscale, are discussed in Section 2. The new interface mesomodel is presented in Section 3. Finally, some results of simulations performed with and without the ply/interface coupling are presented in Section 4 in order to illustrate the role of such interaction in the development of subcritical damage and failure in laminated composites.

2 Ply/interface coupling on the mesoscale

The mesoscale description of laminated composites considered here is the damage mesomodel developed at LMT-Cachan [4,5]. It is based on the assumption that any laminate can be described as a stack of two mesoconstituents: the ply and the interface. Both of these constituents are modeled as continuous media, using damage variables to mirror the effect of the elementary degradation mechanisms.

In particular, transverse cracking within the plies is modeled by introducing a single, microscale variable to describe the crack morphology: the microcracking rate in the ply ρ. Micromechanical simulations on an elementary cell and an energetic equivalence between the micro- and the mesoscales allow to determine three mesoscale damage variables, associated to the loss of stiffness generated by the transverse cracks [5].

Interface delamination, on the other hand, is modeled via a classical cohesive model [6], in which three damage variables, d_I, d_{II} and d_{III}, account for the three delamination modes (Mode I, Mode II and Mode III).

Micromechanical simulations allow to highlight the effect of the cracks in the adjacent plies on the behavior of an interface [7]. Two sources of coupling are present:

1. the presence of cracks within the adjacent plies influence the mesoscopic stiffness of an interface;
2. the stress concentration on the tip of the ply cracks can generate interface delamination.

Both elements are introduced in the new interface model:

1. the dependence of the interface damage variables d_I, d_{II} and d_{III} on the microcracking rate ρ in the adjacent plies;
2. a criterion for delamination initiation associated to the adjacent plies' stress and damage state.

In the following, the new interface model thus constructed is presented in brief, including the simplifications introduced in the previous version [3]. A full description of the model is given in [2].

3 Construction of the new interface mesomodel [2]

The new model is derived from 3D calculations on a cell following the micro-meso bridge introduced and developed in [4] and [7].

3.1 Influence of the cracks in the adjacent plies on the mesoscopic interface stiffness

The equivalence between the micro- and the mesoscale interface energy on an elementary cell allows to obtain the following expressions for the interface damage variables:

$$\begin{cases} d_I \\ d_{II} = \dfrac{d_I + (1-d_I)(A_{\text{sup}} + A_{\text{inf}})\sin^2(\theta/2)}{1 + (1-d_I)(A_{\text{sup}} + A_{\text{inf}})\sin^2(\theta/2)} & with \quad A_i = \dfrac{a(\rho_i)}{1-a(\rho_i)} \\ d_{III} = \dfrac{d_I + (1-d_I)(A_{\text{sup}} + A_{\text{inf}})\cos^2(\theta/2)}{1 + (1-d_I)(A_{\text{sup}} + A_{\text{inf}})\cos^2(\theta/2)} \end{cases} \qquad (1)$$

Here, ρ_{sup} and ρ_{inf} are the microcracking rates in the upper and lower plies and θ is the angle between them. In a previous version of the interface model, Equation (1) was simplified to:

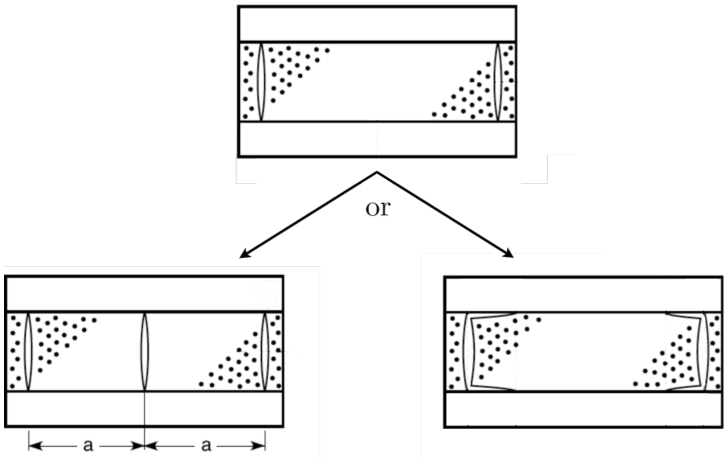

Figure 1. Two possible scenarios: new crack creation in the ply (left) or delamination propagation in the interface (right) [9].

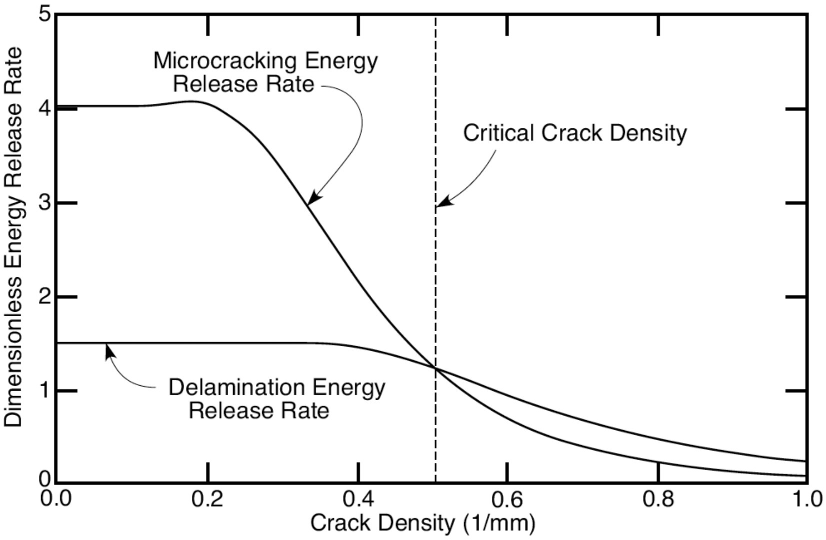

Figure 2. Dimensionless energy release rates associated to delamination and transverse cracking as a function of the microcracking rate in the ply [9].

$$\begin{cases} d_I \\ d_{II} = d_I + (1 - d_I)a_i\bar{\rho}\sin^2(\theta/2) \\ d_{III} = d_I + (1 - d_I)a_i\bar{\rho}\cos^2(\theta/2) \end{cases} \tag{2}$$

where $\bar{\rho}$ represents the mean microcracking rate in the adjacent plies. In this case, the influence of the cracking states in the adjacent plies where not separated, which may lead to a wrong estimate of the mesoscopic interface stiffness in case of very different crack densities.

3.2 An in-plane criterion for delamination

The second and most important source of coupling between the ply and interface behavior is the creation of delaminations starting from the tip of the transverse ply cracks. This phenomenon is well documented experimentally [8]: once the microcracking rate within a ply has reached a given value (saturation), no more ply cracks are created and local delaminations start developing on the tip of the transverse cracks. The microcracking rate at saturation, ρ_s, can be determined experimentally from $[0/90_n]_s$ tensile tests.

A micromechanical interpretation of this phenomenon was given by Nairn [9]. The creation of a new, discrete crack is predicted by comparing the strain energy release rate associated to crack formation to a critical material value. Since cracks can develop either in the ply or in the interface, it is necessary to consider each of the two energy release rates (transverse cracking / delamination) in order to determine which phenomenon will occur (see schema in Figure 1).

Figure 2 shows the evolution of the strain energy release rates with microcracking rate, as computed in [9]. At the beginning of loading, for low microcracking rates, the energy release rate associated with the creation of cracks within the ply is much higher than the one associated with delamination. Thus, cracks are created in the ply and not in the interface. When the microcracking rate in the ply increases, the energy release rate associated with transverse cracking decreases, until it reaches the value of the one associated to delamination. At this point, delamination becomes more energetically advantageous, thus the microcracking rate within the ply saturates and delamination spreads across the interface.

A first, simplified description of this phenomenon within the interface mesomodel, used in [3], was an heuristic criterion based on experimental observations: when the mean microcracking rates in the two adjacent plies reaches a threshold value, the interface is considered as fully damaged:

$$\overline{\rho} = \rho_s \Rightarrow d_I = d_{II} = d_{III} = 1 \tag{3}$$

With this definition, microcracking rate has to reach saturation in both adjacent plies to induce delamination in the interface. In many practical cases, such as $[0/90_n]_s$ tensile tests, only some of the plies, loaded in the transverse direction, develop transverse cracks, and these are largely sufficient to induce interface delamination. For this reason, a criterion taking into account separately each of the adjacent plies needs to be used.

In the present model, such criterion is defined starting from the idea in [9]. Unitary strain energy release rates for transverse cracking and delamination are determined from simulations on an unit cell and a criterion for interface delamination based on the stress and damage state of each of the adjacent plies is defined. Since delamination induced by transverse cracks appears to be an unstable phenomenon, once this criterion is satisfied for either of the adjacent plies, the interface is considered as fully delaminated.

The present model differs slightly from [9] in the choice of the material parameters to be identified. Indeed, Figure 26. implies that the critical strain energy release rate for the ply and for the interface are the same (since crack saturation and delamination initiation occur at the crossing of the two curves). This equality, however, is generally not satisfied [10]. For this reason, in the present model the microcracking rate at saturation is experimentally identified and injected in the strain energy release rates calculations in order to determine the ratio between the critical strain energy release rates for the ply and for the interface. The details of the described procedure are given in [2].

4 An illustration: simulation of open hole tensile tests

In the following, numerical simulation of an open hole tensile test on a quasi-isotropic specimen are used to illustrate the importance of the ply/interface coupling introduced in the interface mesomodel. The test case used is issued from the experimental campaign performed by Wisnom and Hallett on scaled open hole specimens [1]. In-plane and thickness scaling of the specimen lead to very different failure loads and scenarios: in the following, the stacking sequence $\left[45_4/90_4/-45_4/0_4\right]_S$ and in-plane dimensions $127 \times 31{,}75$ mm were selected, since in this case the experimental specimen failure is induced by the interaction of transverse ply cracks and delaminations.

The test is simulated using the damage mesomodel. In order to illustrate the effect of the coupling, the new interface model, as well as a classical cohesive zone interface model, are used in the simulations. The results in terms of global behavior and of evolution of the degradation are compared.

4.1 Global behavior

The global stress/strain curves given by the two simulations are presented in Figure 3. Both curves show a slope change for an imposed deformation of $\varepsilon = 0.38\%$, corresponding to the development of subcritical damage (transverse cracking); however, the behavior after the onset of subcritical damage is different for the two simulations. When the new interface model is used, the simulation predicts a failure stress close to the one observed experimentally ($\sigma_{\max} = 280$ MPa is the simulated value, $\sigma_{\max} = 285$ MPa is the experimental value). When the cohesive zone model without coupling is used, the simulation predicts a higher stress value at failure ($\sigma_{\max} = 310$ MPa).

The introduction of the coupling appears to be important for a correct prediction of the failure load. A more detailed observation of the damage evolution predicted by the two simulations allows to understand its role on the development of the final failure scenario.

4.2 Damage evolution

The results of the two simulations are compared at three loading levels, corresponding to key points in the damage evolution:

- $\varepsilon = 0.38\%$: transverse cracking appears in the plies and a slope change is observed on the global stress/strain curve (Figure 4);
- $\varepsilon = 0.52\%$: delamination has appeared in all the interfaces (Figure 5);
- $\varepsilon = 0.58\%$: the specimen is broken (Figure 6).

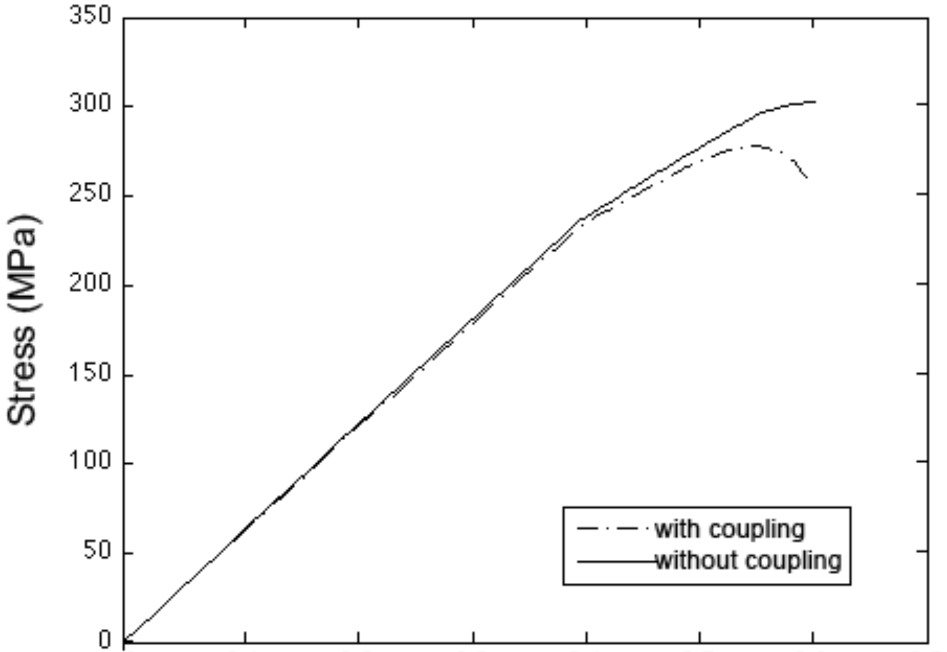

Figure 3. Global stress/strain curves resulting from the simulations with and without coupling model.

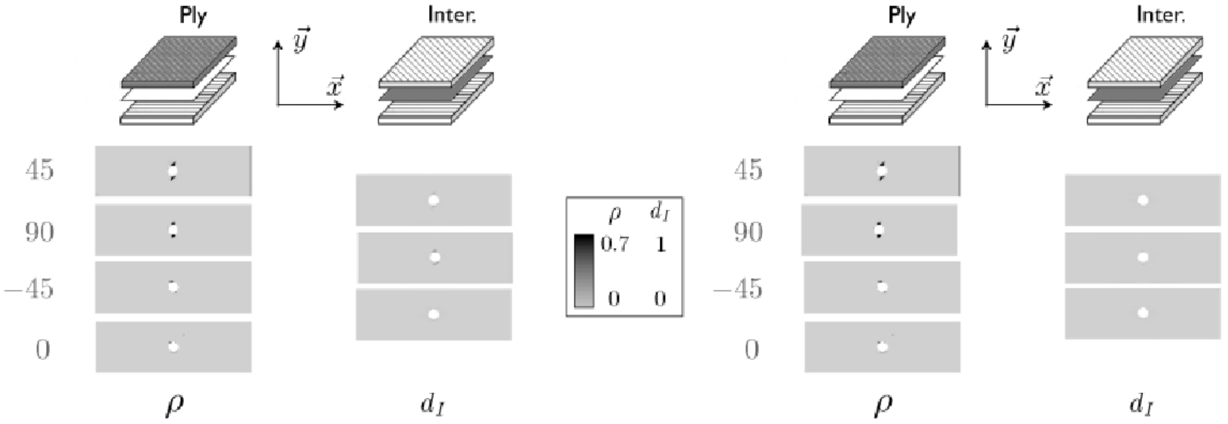

Figure 4. Simulated damage charts with the new interface mesomodel (left) and with the cohesive zone model (right) for an imposed strain of $\varepsilon = 0.38\%$.

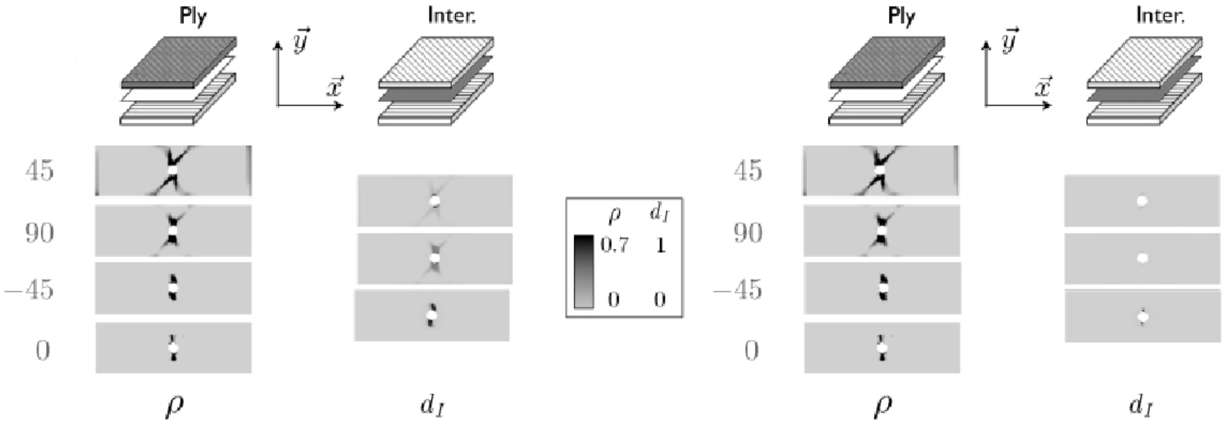

Figure 5. Simulated damage charts with the new interface mesomodel (left) and with the cohesive zone model (right) for an imposed strain of $\varepsilon = 0.52\%$.

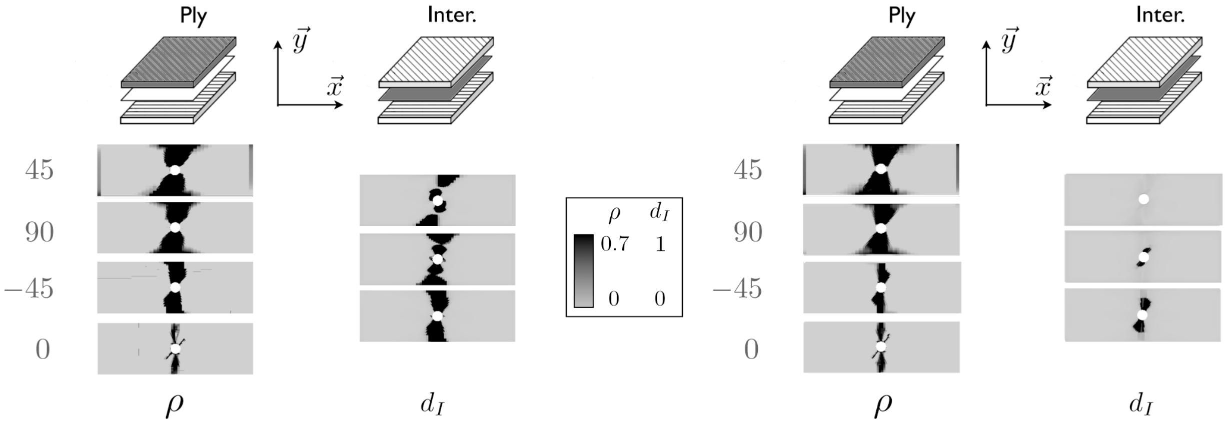

Figure 6. Simulated damage charts with the new interface mesomodel (left) and with the cohesive zone model (right) for an imposed strain of $\varepsilon = 0.58\%$.

The damage charts corresponding to these loading points are presented in Figures 4 to 6. In those, $\rho = 0.7$ represents a fully cracked zone in the ply and $d_I = 1$ depicts a fully delaminated interface.

For $\varepsilon = 0.38\%$, the two models give similar results. Transverse cracks appear in different plies but delamination has not appeared yet.

For $\varepsilon = 0.52\%$, both model predict a transverse cracking behavior in correlation with the experimental observations. However, less delamination is predicted by the classical cohesive interface model.

For $\varepsilon = 0.58\%$, the difference between the two simulations is clear: the new interface mesomodel predicts the development of delamination in all the interfaces and across the width of the specimen. On the contrary, the classical cohesive interface model predicts only a little degradation in the interfaces. Thus, if coupling with the ply behavior is not included, the interface cohesive zone model may fail to predict the correct failure scenario (and, thus, the correct failure load, as it was seen in the previous section).

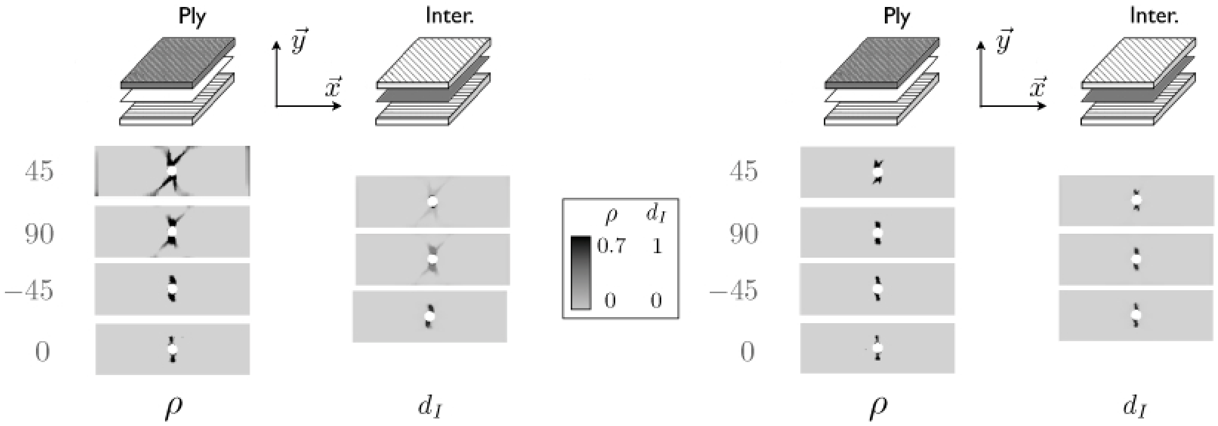

Figure 7. Simulated damage charts with the new (left) and simplified (right) model for an imposed strain of $\varepsilon = 0.52\%$.

4.3 The simplified interface mesomodel

The previous sections allowed to illustrate the importance of introducing ply/interface coupling within the interface mesomodel. As it can be seen in the damage charts, the introduction of such coupling modifies the interface behavior, but seems to interfere little with the evolution of transverse cracking. This was not the case for the simplified version of the interface mesomodel, used in [3].

The damage charts at $\varepsilon = 0.52\%$ obtained with the present (left) and the simplified (right) versions of the coupling are given in Figure 7. The use of the heuristic criterion based on saturation of the mean microcracking rate predicts an earlier development of delamination with respect to the criterion used here. This, in turn, seems to delay the development of transverse cracking, both with respect to the new interface mesomodel and to the classical cohesive zone model.

5 Conclusion

A new interface mesomodel, taking into account the influence of transverse cracking in the adjacent plies, is defined from micromechanical considerations. It allows to describe the effect of ply cracks on the mesoscopic stiffness of the interface, as well as the delamination induced by in-plane loadings via stress concentrations on the tip of the transverse cracks. The importance of introducing such a coupling and its effect on the prediction of the failure load and scenario of composite structures is illustrated via simulations of an open hole quasi-isotropic tensile specimen.

References

[1] Wisnom M.R., Hallett S.R. The role of delamination in strength, failure mechanism and hole size effect in open hole tensile tests on quasi-isotropic laminates. *Composites: Part A*. **40**, pp. 335-342 (2009).

[2] Ladeveze P., Daghia F., Abisset E., Lemauff C. On the intra/interlaminar coupling of laminated composite: modeling and identification. *Composites: Part A*, **submitted.**

[3] Abisset E., Daghia F., Ladeveze P. On the validation of a damage mesomodel for laminated composites by means of open-hole tensile tests on quasi-isotropic laminates. *Composites: Part A*. **42**, pp. 1515-1524 (2011).

[4] Ladevèze P. *Multiscale modelling of damage and fracture* processes in composite materials in « Multiscale computational damage modelling of laminated composites », edited by Tomasz Sadowski. CISM Courses and Lectures, **474**. (2005).

[5] Lubineau G., Ladevèze P. Construction of a micromechanics-based intralaminar mesomodel and illustrations in ABAQUS/Standard. *Computational Mechanics Science*. **43**, pp. 137-145 (2008).

[6] Allix O., Ladevèze P. Interlaminar interface modeling for the prediction of delamination. *Composite Structures*. **22**, pp. 235-242 (1992).

[7] Ladevèze P., Lubineau G., Marsal D. Towards a bridge between the micro-and mesomechanics of delamination for laminated composites. *Composites Science and Technology*. **66**, pp. 698-712 (2006).

[8] Crossman F.W., Wang A.S.D.. *The dependence of transverse cracking and delamination on ply thickness in Graphite/Epoxy laminates* in “Damage in Composite Materials” edited by Reifsnider K.L. American Society for Testing and Materials. Pp. 118-139 (1982).

[9] Nairn J.A., Hu S. The initiation and growth of delaminations induced by matrix microcracks in laminated composites. *International Journal of Fracture*. **57**, pp. 1-24 (1992).

[10] Nairn J.A. *Matrix Microcracking in composites* in “Comprehensive Composite Materials”, edited by Taljera R. and Manson J.-A. Elsevier Science, **2**, pp. 403-432 (2000).