Modelling of delamination onset and growth in damaged layered composite material

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Abstract

Tools for simulate the delamination onset and propagation in composite structure, one of the most critical damage in these materials, are not plainly satisfactory due to a lack of knowledge on the interaction with other damage like ply damage. Several theoretical studies underline the influence of transverse cracks and their local delamination on the evolution of the delamination front. Recently, an experimental approach has confirmed that the more the adjacent plies are damaged, the less the apparent tenacity of the interface is.

In this work, a non local formulation has been used not to avoid localisation problem but to share information between surface and volume elements thanks to additional nodal degrees of freedom induced by the non local framework. A non local cohesive zone model and the associated interface behaviour law tacking into account the local delamination have been developed. The ply behaviour is also based on a non local formulation and on previous local formulation that takes into account the thickness effect of the ply.

Theses models are then applied to the simulation of the damage growth on a notched coupon and on an open hole plate in order to demonstrate the contribution of this approach.

Mots Clés : Elément de zone cohésive, délaminage, endommagement, fissuration transverse, CMO
Keywords : Cohesive zone model, delamination, damage, transverse craking, CFRP

1 Introduction

Damage and rupture of composite materials are due to complex coupled mechanisms. For example, the delamination onset and growth are not still fully understood since several theoretical studies [1,2] underline the influence of ply damage and more precisely local delamination on the delamination growth. In order to not only experimentally demonstrate this coupling but also propose an identification procedure of a model taking into account such coupling, a recent experimental procedure has been developed and tested at Onera [3]. The fracture characterization of delamination is indeed defined by the toughness of the interface in a fracture mechanics point of view [4]. These material parameters are measured by classical fracture mechanical tests like DCB (double cantilever beam), ENF (end notch flexure) or MMF (mixed mode flexure). Although these tests give accurate results, they can not permit to study the influence of intralaminar damage and more precisely of local delamination on the delamination growth. These tests need to insert film in order to generate starter crack during the manufacturing process that does not allow damaging the composite preliminary by another classical mechanical test (tensile or bending tests). The general principle of our experimental test is presented on Figure 1.

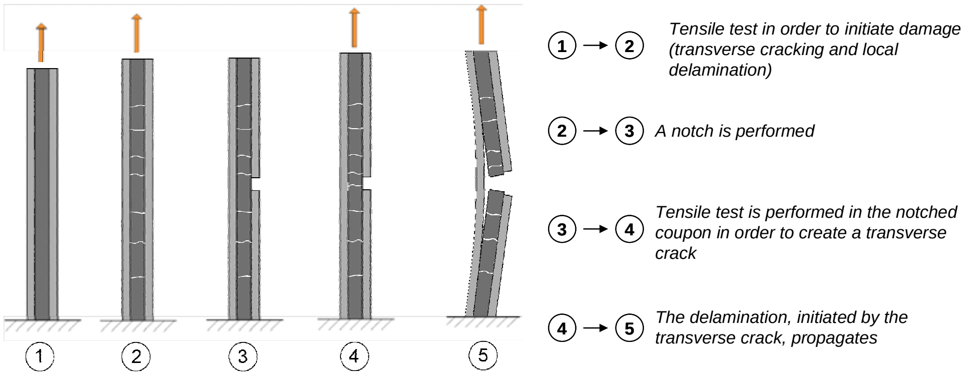

Figure 1. Principe de l'essai de traction sur plaque entaillée pour l'étude de la propagation du délaminage en présence d'endommagement dans les plis adjacents

In order to overcome the limitation of classic fracture mechanical tests, this experimental procedure is a succession of two traction loadings. During the first phase, the 90° plies of the cross ply laminate tested are damaged. Thanks to previous works [5] on the chosen carbon/epoxy laminate (T700/M21), the damage level (transverse cracks rate and local delamination rate) could be driven. The analyse of this test campaign thanks to virtual testing computations [3] takes into account (*i*) the delamination onset and growth by cohesive zone models [6] and (*ii*) the equivalent behaviour of the damaged plies, permit to demonstrate the decrease of the matrix toughness (Figure 2).

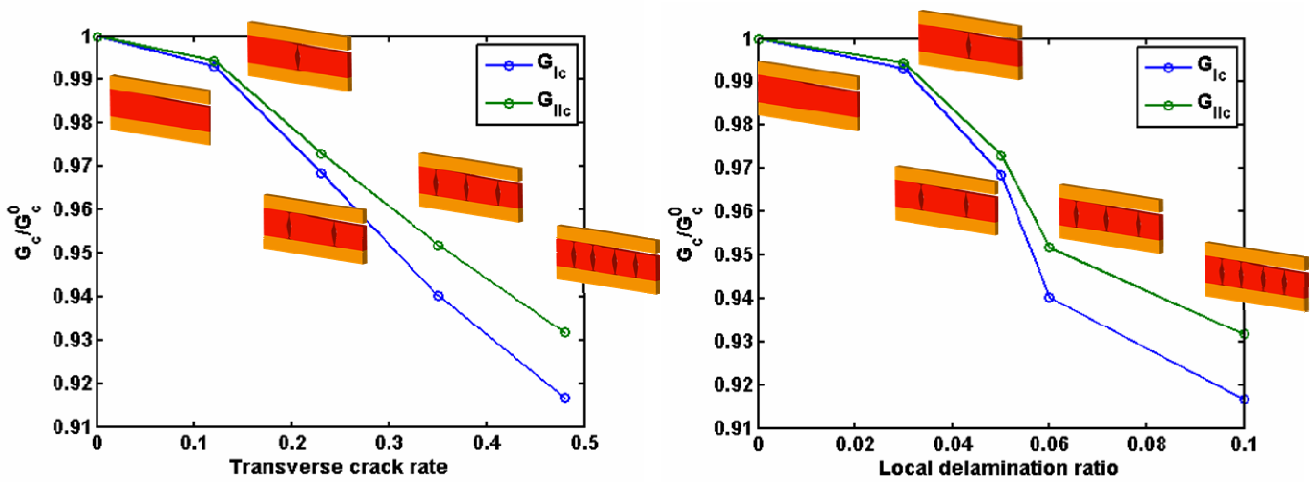

Figure. 2. Evolution de la dégradation des ténacités apparentes en mode I et II de l'interface 0°/90° en fonction de l'endommagement du pli à 90° d'une stratification croisée

This study underlines the necessity to couple the delamination growth at the interface with the damage behaviour of the ply. Nevertheless, the implementation in a Finite Element code of this type of coupling is not a trivial task. The use of a non local formalism permits us to share information between volume element and interface element. This non local formalism will be described in the first part of this article by presenting the ply behaviour and the interface behaviour developed and implemented in a FE house code ZéBuLoN. In a second part, the contribution of this damage behaviour will be demonstrated by the simulation of several structural examples.

2 Modélisation non locale

The first non local approaches are proposed by Pijaudier-Cabot et Bazant [7]. Nevertheless, the implementation of such formalism is quite difficult in a finite element code and the implicit gradient proposed by Peerlings [8] and adapted by Germain [9] for composite material was preferred. In this formalism, the degrees of freedom of the problem are composed of classical nodal displacement variables and of additional ones named non local variables because the time evolution of these variables not only depend on the local state but also in the neighbourhood of the considered point. The first ones are the solution of the classical mechanical problem and the second ones are governed by a diffusion equation linking the non local variables added (f_{nl}) to local variable (f_l) computed by the behaviour law at each Gauss point and a null flux condition is usually retained on the boundaries of the domain Ω :

$$\begin{cases} f_{nl} - c\nabla^2 f_{nl} = f_l & \text{on } \Omega \\ \dfrac{\partial f_{nl}}{\partial n} = 0 & \text{on } \partial\Omega \end{cases} \tag{1}$$

This type of formalism was originally proposed in order to avoid mesh size dependency problem due to the use of softening behaviour but needs to identify a new material parameter *c* which has the dimension of a length squared. In our approach, this formalism is more used for the possibility to share easily information between elements thanks to the additional degrees of freedom than avoid localisation problem.

In previous work [5], a mesoscopic model into the continuum damage mechanics frameworks has been developed. This model is able to predict the transverse crack rate and the local-delamination rate due to the transverse cracks. The method developed is based on this approach in order to develop a damage behaviour law of the interface tacking into account the presence of ply damage on the delamination propagation. The principle of the method is quite simple. Thanks to the knowledge of the transverse crack rate in adjacent volume elements, the local delamination rate ($\bar{\mu}$) in the interface element is computed. Hence the effective damage variable of the interface ($\tilde{\lambda}$) is defined by:

$$\tilde{\lambda} = \lambda + \bar{\mu} \tag{2}$$

where λ is the classical damage variable computed by the cohesive zone model. In order to use the information present in adjacent element, it is necessary to propose in a first step a non local formulation of the previous model [5] and then a new formulation of the interface behaviour law.

2.1 Modélisation du comportement du pli

Although the previous model takes into account the viscous behaviour of the matrix, each ply is considered first of all as an elastic transversely isotropic material. Its equivalent elastic compliance tensor $\tilde{\underline{\underline{S}}}$ is defined as a function of the normalized crack density ($\bar{\rho}$):

$$\tilde{\underline{\underline{S}}} = \underline{\underline{S}}^0 + \bar{\rho}\,\underline{\underline{H}}_1^{\bar{\rho}} + \bar{\rho}^2\,\underline{\underline{H}}_2^{\bar{\rho}} \tag{3}$$

where $\underline{\underline{S}}^0$ is the initial compliance tensor of the ply and $\underline{\underline{H}}_1^{\bar{\rho}}$ and $\underline{\underline{H}}_2^{\bar{\rho}}$ are damage effect tensors. These tensors are identified by virtual testing [10] and permit to define the following coefficient:

$$\underline{\underline{H}}_i^{\bar{\rho}} = \begin{bmatrix} h_{11}^{\bar{\rho}i} S_{11}^0 & h_{12}^{\bar{\rho}i} S_{12}^0 & h_{13}^{\bar{\rho}i} S_{13}^0 & & & \\ h_{21}^{\bar{\rho}i} S_{21}^0 & h_{22}^{\bar{\rho}i} S_{22}^0 & h_{23}^{\bar{\rho}i} S_{23}^0 & & & \\ h_{31}^{\bar{\rho}i} S_{31}^0 & h_{32}^{\bar{\rho}i} S_{32}^0 & h_{33}^{\bar{\rho}i} S_{33}^0 & & & \\ & & & h_{44}^{\bar{\rho}i} S_{44}^0 & & \\ & & & & h_{55}^{\bar{\rho}i} S_{55}^0 & \\ & & & & & h_{66}^{\bar{\rho}i} S_{66}^0 \end{bmatrix} \tag{4}$$

The evolution of the damage variable $\bar{\rho}$ is defined thanks to the following relation:

$$\bar{\rho} = K\sqrt{Y_{\bar{\rho}}} \tag{5}$$

in which *K* is material parameter and $Y_{\bar{\rho}}$ is a non local variable. $Y_{\bar{\rho}}$ is computed thanks to Eq. (1) in which the local variable is the thermodynamic force $y_{\bar\rho}$ defined by the following relation:

$$y_{\bar\rho} = \gamma_{\bar\rho} \left\langle \sqrt{y_{\bar\rho_I}} - \sqrt{y^S_{\bar\rho_I}} \right\rangle_+ + \left(1-\gamma_{\bar\rho}\right) \left\langle \sqrt{y_{\bar\rho_{II}}} - \sqrt{y^S_{\bar\rho_{II}}} \right\rangle_+ \tag{6}$$

with:

$$\begin{cases} y_{\bar\rho_I} = \dfrac{h_{22}^{\bar\rho 1}}{2} C_{22}^0 \left\langle \varepsilon_{22} \right\rangle_+^2 \\ y_{\bar\rho_{II}} = h_{66}^{\bar\rho 1} C_{66}^0 \varepsilon_{12}^{\;2} \end{cases} \tag{7}$$

In the precedent relations, $\langle\ \rangle$ are the Mc Cauley brackets, $\gamma_{\bar\rho}$ is a material parameter and $\underline{\underline{C}}^0$ is the initial stiffness tensor.

These parameters are $h_{22}^{\bar\rho 1}$ and $h_{66}^{\bar\rho 1}$ are defined in relation (4). $y^S_{\bar\rho_I}$ and $y^S_{\bar\rho_{II}}$ define the onset of damage in mode *I* and *II* thanks to a mixed criterion [10,11]:

$$\begin{cases} y^S_{\bar\rho_I} = \max\left[\dfrac{y^E_{o_I}}{h}, y^\sigma_{o_I} \right] \\ y^S_{\bar\rho_{II}} = \max\left[\dfrac{y^E_{o_{II}}}{h}, y^\sigma_{o_{II}} \right] \end{cases} \tag{8}$$

in which *h* is the thickness of the ply, $y^E_{o_I}$ (respectively $y^E_{o_{II}}$) are the onset parameters for an energy criterion in mode I (respectively mode II) and $y^\sigma_{o_I}$ (respectively $y^\sigma_{o_{II}}$) are the onset parameters for a stress criterion in mode I (respectively mode II). The previous relation permits to take into account the ply thickness effect.

2.2 Modélisation du comportement de l'interface

The non local interface behaviour law is based on the local formulation proposed by Tvergaard [6]. In such behaviour law, the relationship between the relative normal and tangential displacement at the interface (u_n, u_t) and their corresponding tractions components (T_n, T_t) depends on a damage variable λ and its generic form is:

$$\begin{cases} T_n = E\dfrac{u_n}{\delta_n} F(\lambda) & \text{if } u_n \geq 0 \\ T_n = KE\dfrac{u_n}{\delta_n} & \text{if } u_n < 0 \end{cases} \quad \text{and } T_t = \alpha E \frac{u_t}{\delta_t} F(\lambda) \tag{9}$$

where δ_n and δ_t are the normal and tangential displacements at the complete separation for pure normal and tangential modes. *E*, αE and KE are the initial stiffness of the interface for tensions, shear and compressive loading. In the Tvergaard model, the damage parameter is defined as the maximum value of the norm of the displacement and the function $F(\lambda)$:

$$F(\lambda) = (1-\lambda)^2 \text{ with } \lambda = \max_{\tau < t} \sqrt{\left\langle \frac{u_n}{\delta_n} \right\rangle^2 + \left(\frac{u_t}{\delta_t} \right)^2} \tag{10}$$

In Eq. (10), the Mc Cauley bracket $\langle\ \rangle$ indicates that the negative normal displacement has no effect on the damage evolution.

The proposed non local formulation only modifies relations Eq (9) by replacing λ by $\tilde{\lambda}$ defined previously (Eq 2) and add the following formulation for the evolution of the local delamination rate:

$$\overline{\mu} = \max_{\tau<t}\left(1 - e^{-\frac{Y_{\overline{\rho}}^{eff}\sqrt{Y_{\overline{\rho}}^{eff}}}{k}}\right) \tag{11}$$

in which k is a material parameter and $Y_{\overline{\rho}}^{eff}$ is the effective non local thermodynamic force since the interface could have two adjacent damaged plies $\left(Y_{\overline{\rho}}^{up}, Y_{\overline{\rho}}^{down}\right)$. For simplicity, the definition of this variable is:

$$Y_{\overline{\rho}}^{eff} = \max\left(Y_{\overline{\rho}}^{up}, Y_{\overline{\rho}}^{down}\right) \tag{12}$$

The Figure 3 presents the principle of the non local element developed and implemented in the in house FE code ZéBuLoN.

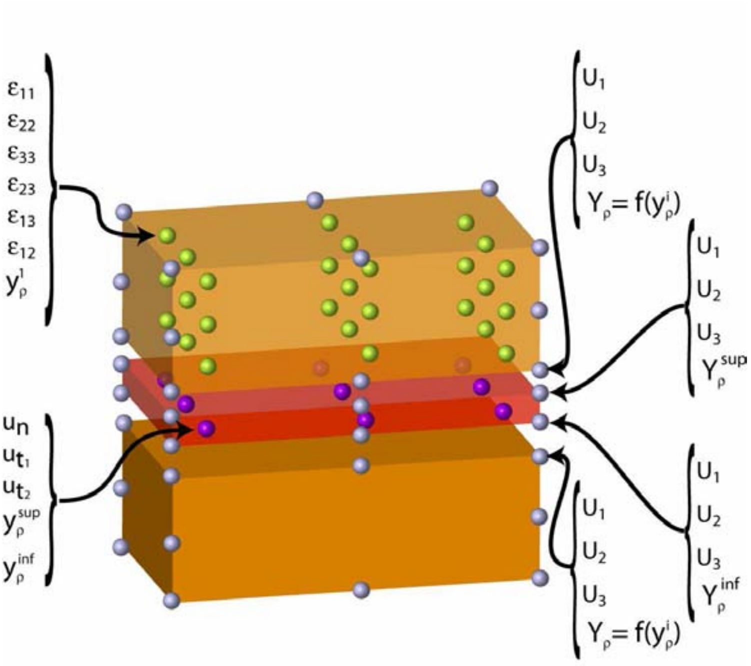

Fig. 3. Sketch of the non local elements for the interface and the ply

In order to show the influence of the local delamination rate on the behaviour of the interface, the Figure 4 presents the normal interface behaviour as a function of the local delamination rate. The higher the local delamination rate is, the sooner the interface fracture is due to a decrease of the interface toughness.

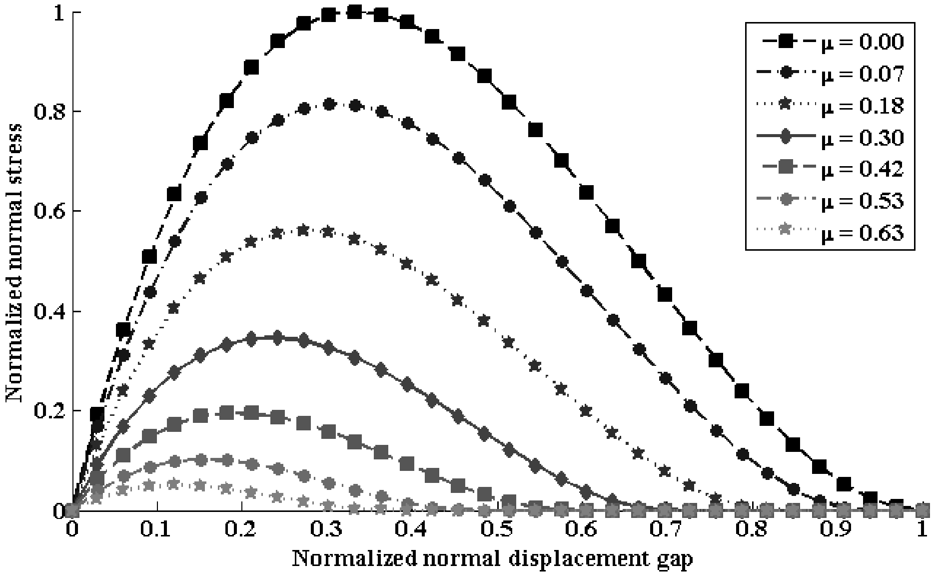

Fig. 4. Local normal interface behaviour as a function of local delamination rate.

3 Applications

3.1 Plaque entaillée

The developed model has been used to simulate the traction test of a grooved cross ply laminate ($[0_2/90_2]_s$) presented in the introduction (Figure. 1). In a first step, we compute the damage present in the 90° plies due to the first traction loading. In a second step, an other traction loading is applied on the specimen in which the notched is taking into account thanks to a "remove-element" technique. The Figure 5 presents our numerical results for several level of ply damage. These simulations demonstrate that the coupling between ply and interface damage permit to have a sooner damage and a quicker delamination growth.

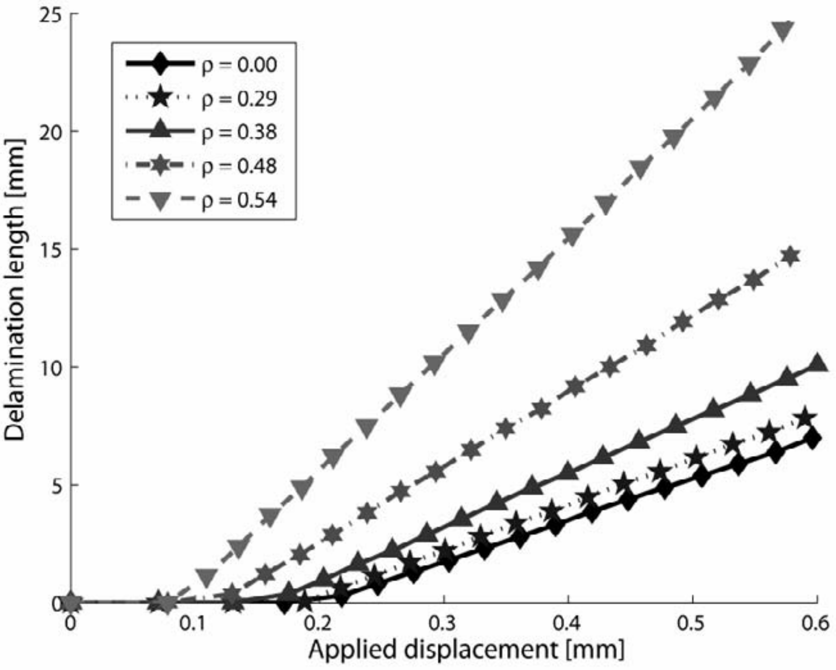

Fig. 5. Influence of the ply damage on the delamination length.

On the Figure 6, a partial comparison between experimental and simulation results are presented. This figure plots the evolution of the delamination length as a function of the ply damage level for an imposed displacement. The gap between experimental and simulation results is due to the small deformation hypothesis retained in computation. The non local elements developed in the ZeBuLoN code don't, in fact, take into account the large displacement. Nevertheless, the simulation results underline a qualitative agreement with the experimental ones and seem to validate the proposed formulation.

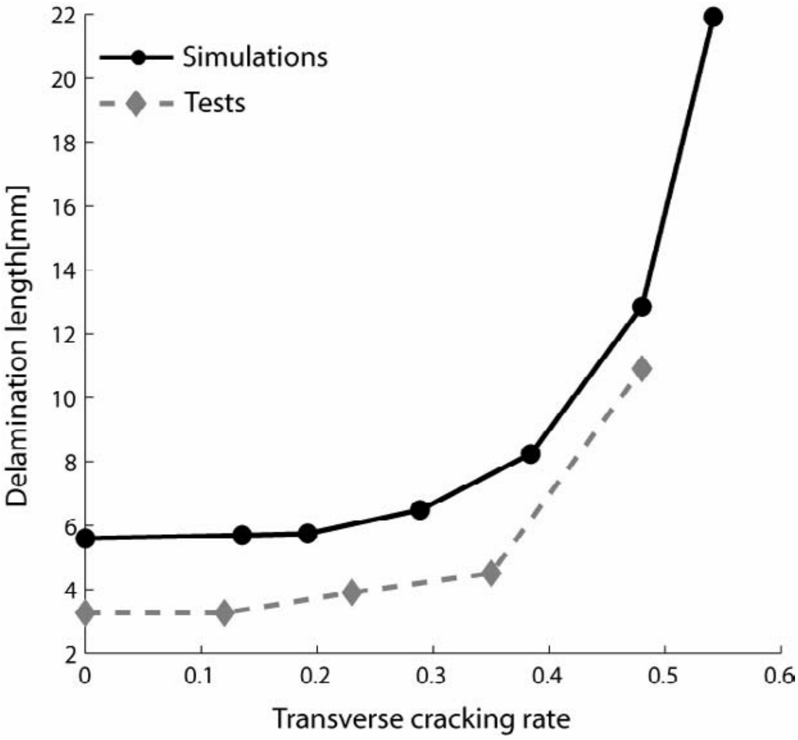

Fig. 6. Comparison between experimental and simulation results for an applied displacement of 0.52mm

3.2 Open hole plates

In this part, the model proposed in the pervious section has been applied on the simulation of open hole plates. In order to demonstrate the influence of the coupling between ply damage and the delamination growth, three simulations have been proceeded with different values of the material parameter k (Eq 11). In the first computation, the coupling is quite null since the value of k is very high (k=1000). In the two other simulations, the k value is decreasing (k=0.5 for the leak coupling and k=0.1 for the strong coupling) and imply an increasing coupling. The Figures 8-10 present the evolution of the different damage mechanisms taken into account in our computations. In order to perform these simulations in a reasonable computation time, the computation strategy proposed by Vandellos [12] has been used.

The use of cohesive zone models implies an increasing of the computational cost but permit to predict the onset and the growth of the delamination length. On the other hand, the use of non local elements increase the number of degrees of freedom and also imply an increase of the computation time. In the studied case, volume and surface non local elements are utilized in order to simulate the ply damage and the delamination growth. In the aim of test and validate our developed approach on more complex cases with a reasonable computational cost, it is necessary to propose improved computation strategy. The Figure 7 presents the retained mesh and the different type of elements used.

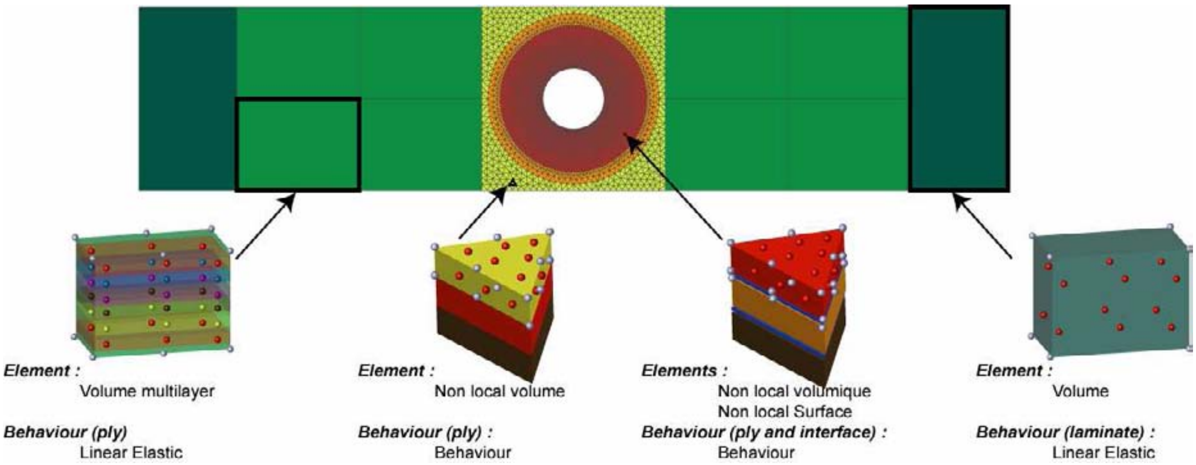

Fig. 7. Mesh retained and type of element used

In the region named “zone of interest” (in yellow, red and orange on the Figure 7), every ply damage mechanisms are modelled with a ply by ply volume mesh of the structure. The delamination fracture could only appear in the red zone since cohesive zone models are introduced between every plies. The non local approach presented in the previous section are only used in this zone. Outside of this “zone of interest”, the mesh is composed of multilayer and standard volume elements. The ply behaviour is supposed linear elastic in the multilevel element whereas the homogenous equivalent behaviour of the laminate is considered in volume elements. The laminate stacking sequence in the simulation is a cross ply laminate (0/90]$_s$).

The Figure 8 presents the delamination evolution as a function of the applied displacement to the coupon and of the considered coupling.

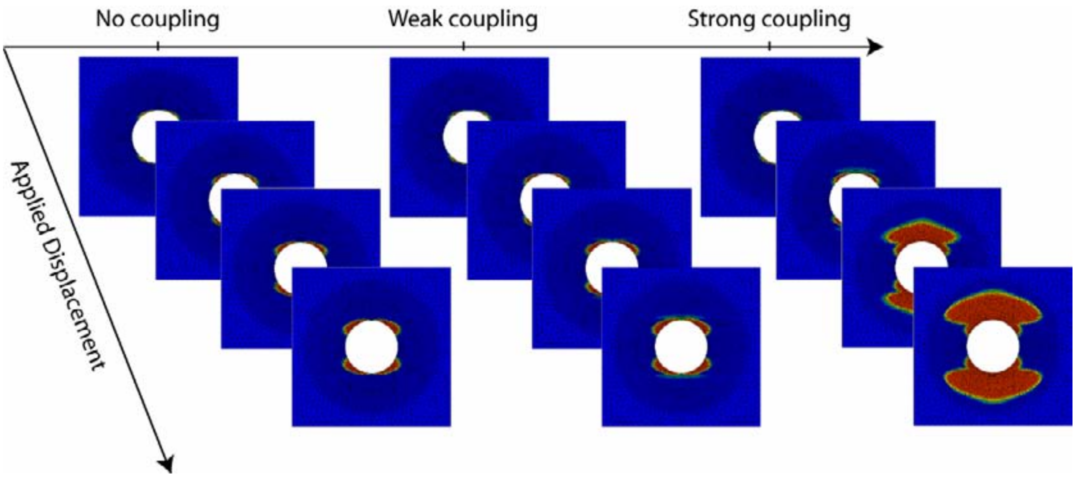

Fig. 8. Evolution the delamination front as a function of the applied displacement

On the opposite of the previous simulation, the delamination onset is very few influenced by the presence of damage in adjacent plies (Figs 9-10). It is due to the low-level of transverse cracking rate and local delamination which depends on the value of the *k* parameter. Nevertheless, the influence of intraply damage is very clear on the delamination growth for higher displacement loading and for higher level of intraply damage. The delamination front is also modified by the pattern of local delamination (Fig. 8 and Fig.10).

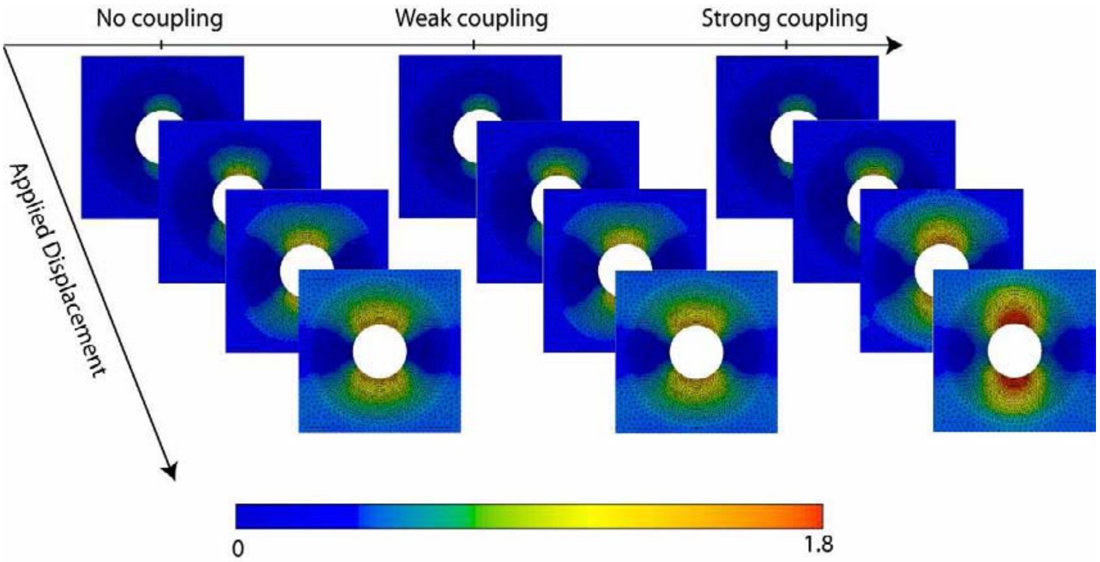

Fig. 9. Evolution of the transverse cracking in the 90° plies as a function of the applied displacement

Moreover, the Fig. 9 underlines the influence of the delamination growth on the ply damage kinetic. The 90° plies transverse cracking level is higher for a strong coupling than for a weak one. At last, the Fig. 10 demonstrates that the local delamination field is governed by the *k* value and by the transverse cracking field. Although the ply damage level is high in the adjacent plies, the local delamination is close to zero for a very high value of *k*. For lower value, the maximum of local delamination rate could reach a value of 0.2 corresponding to a 20% decrease of the interface mechanical properties.

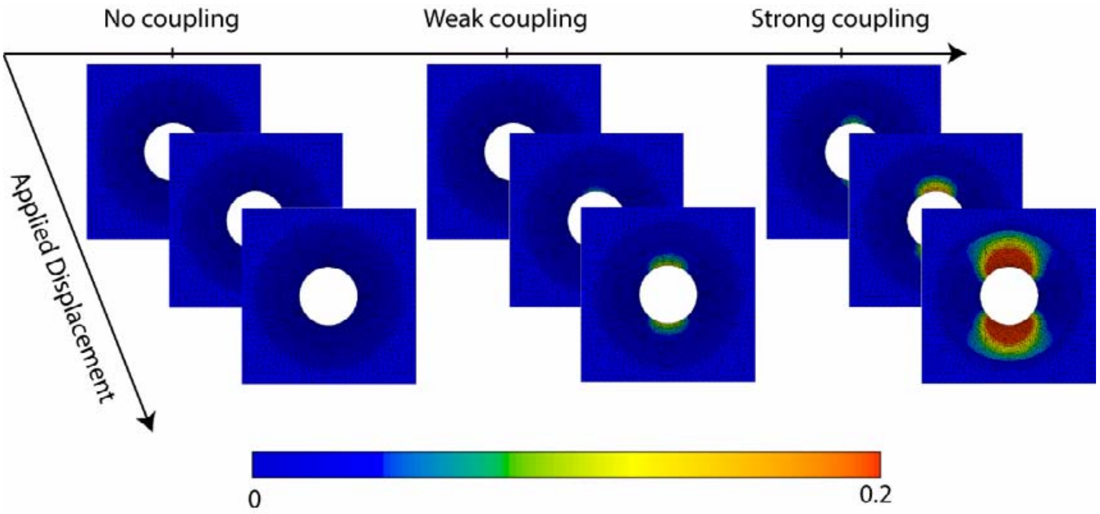

Fig. 10. Evolution of the local delamination as a function of the applied displacement

4 Conclusion

In this article, a non local model for the ply and the interface has been proposed in order to take into account the influence of the ply damage on the onset and growth of the delamination. The ply behaviour is based on a previous formulation [5] which already takes into account the ply thickness effect. The interface behaviour is based on the Tvergaard model [6] which is only modified by the definition of the damage variable. An effective damage variable of the interface is simply defined by the sum of the classic damage and the local delamination rate due to the transverse cracking rate present in adjacent plies. The non local formulation of the element permits to share information between volume and surface element.

The propose model has been used in the simulation of two structures. In the first one, the formulation permits to observe a qualitative agreement with experimental results on the notched coupon. The onset and the propagation of the delamination are modified by the ply damage and more particularly by the local delamination rate. The development of a large displacement non local element should give a complete comparison with the experimental campaign and an identification protocol for the proposed formulation.

In the second application, the influence of *k* parameter has been demonstrated on three simulations of the delamination growth in a open hole plate. As for the notched coupon, the delamination growth is accelerated by the presence of ply damage in adjacent plies. Nevertheless the onset is not sooner for the three simulations whatever the value of the *k* parameter. For the studied case, the onset of ply damage is very similar to delamination one that a very low-level of local delamination at the onset of delamination. Nevertheless the ply damage fields in adjacent plies have an important influence not only on the delamination growth but also on the delamination front. This application has also demonstrated the influence of delamination on the ply damage kinetic. The longer the delamination fracture is, the higher the level of ply damage is.

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