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DAMAGE MODELING OF LAMINATED COMPOSITES: VALIDATION OF THE INTER-LAMINAR DAMAGE MODEL OF SAMCEF AT THE COUPON LEVEL FOR UD PLIES

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Abstract. In this paper, the composite material damage model available in SAMCEF for delamination is validated by comparing simulation and tests results, at the coupon level. The formulation is based on the cohesive elements approach. The parameter identification is discussed. Laminated composites with unidirectional plies of different orientations are studied. It is demonstrated that, in a general case, inter-laminar damage modeling is not enough and intra-laminar damage (that is damage inside the plies) must also be taken into account in the problem.

1 INTRODUCTION

In order to propose predictive simulation tools, it is important to use material models able to represent the different modes of degradation of the laminated composite structure. Most of the time damage at the interface between the plies, that is delamination, is taken into account in the model. This point is addressed in this paper.

Although different modeling and analysis approaches exist in the literature and in commercial software [1-6], the cohesive element formulation and the associated damage model available in the SAMCEF finite element code for modeling delamination of laminated composites are here considered [7]. The approach is based on continuum damage mechanics and was initially developed by the Ladevèze's team in Cachan [8]. The damage model is assigned to some interface elements inserted between the plies to represent their possible de-cohesion and a fracture criterion is used to decide on the inter-laminar crack propagation.

Using such cohesive elements in the analysis allows estimating not only the propagation load but also to predict the failure load, the crack propagation path and the residual stiffness during the fracture process in an automatic way. With this information more accurate safety margins can be assessed.

In this paper, problems at the coupon level are addressed. The inter-laminar damage model is first presented. The basics of the parameter identification procedure of such a material model are briefly explained. Test results at the coupon level on DCB and ENF specimens are used to identify the parameters of the damage law. The obtained values are then validated on a MMB test. It is demonstrated that, in some cases, it is important to model not only the damage at the interface of the plies, but also the damage inside the plies. This is illustrated for the ENF test case. It is therefore decided to also (briefly) present the approach available in SAMCEF for the intra-laminar damage. Even if lots of models are available in the literature [9-14], the formulation developed in SAMCEF for modeling the damages inside the plies is based on the continuum damage mechanics approach initially developed in [15], in which the laminate is made of homogenous plies and damage variables impacting the stiffness of each ply are associated to the different failure modes, representing the fiber breaking, matrix cracking and de-cohesion between fibers and matrix. The advantage of this damage model compared to some others is that a parameter identification procedure can be developed. Moreover, the model is native in SAMCEF and there is no need for additional (not free) plug-ins to solve the progressive damage problem.

2 INTER-LAMINAR DAMAGE MODELING

2.1 Formulation of the inter-laminar damage model

In the approach described in [7,8], interface elements are defined between the plies in the finite element model. The potential associated to the interface elements is given by (1), where the three relevant components of the strain tensor are considered.

$$e_d = \frac{1}{2}\left[k_I^0 \langle \varepsilon_{33} \rangle_-^2 + k_I^0 (1 - d_I) \langle \varepsilon_{33} \rangle_+^2 + k_{II}^0 (1 - d_{II}) \gamma_{31}^2 + k_{III}^0 (1 - d_{III}) \gamma_{32}^2 \right] \quad (1)$$

In (1), k_i^0 (i=I,II,III) represent the stiffness associated to the normal strain and to the two shear effects. Damage variables d_i (i=I,II,III) are defined for each of the three crack solicitation modes as in Figure 1 (opening, shear and sliding modes, for modes I, II and III, respectively).

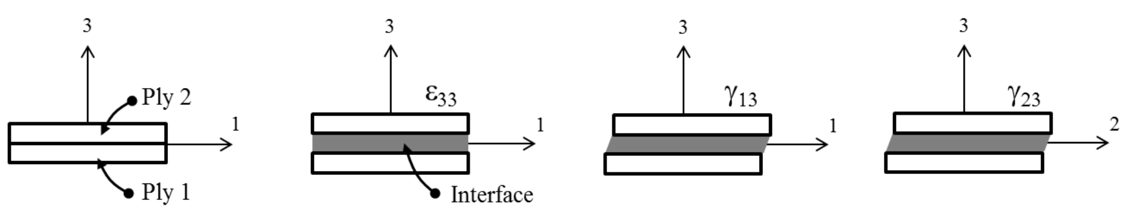


Figure 1: Definition of the interface and crack modes

The value of the damage variable $d_i \in [0,1]$ increases as a function of a thermodynamic force Y_i given by the derivative of the potential (1) with respect to the damage variable. The thermodynamic force represent the effect of the loading in the corresponding mode. For mixed mode loading, the damage evolution is related to the three inter-laminar fracture toughness G_{Ic}, G_{IIc} and G_{IIIc} via an equivalent thermodynamic force Y given in (2), where α is taken equal to 1. It is considered that the three damage variables have the same evolution during the loading, and a single damage variable d associated to Y is then used to represent delamination. In SAMCEF, depending on how d is related to Y, either a polynomial, a bi-triangular or an exponential constitutive law is used in the interface element, as illustrated in Figure 2.

$$Y = \sup_{\tau \le t} G_{IC} \left\{ \left(\frac{Y_I}{G_{IC}} \right)^{\alpha} + \left(\frac{Y_{II}}{G_{IIC}} \right)^{\alpha} + \left(\frac{Y_{III}}{G_{IIIC}} \right)^{\alpha} \right\}^{1/\alpha} \tag{2}$$

For the first two material models of Figure 2, damage appears after a linear elastic behavior of the material's interface (grey region in Figure 2), whereas this is not the case for the exponential law. Initially equal to zero, the damage variable reaches a unit value when all the resistance capacity of the interface has been consumed ($G_i = G_{ic}$ for pure modes, or a combination of the effects via Equation 2 for mixed modes).

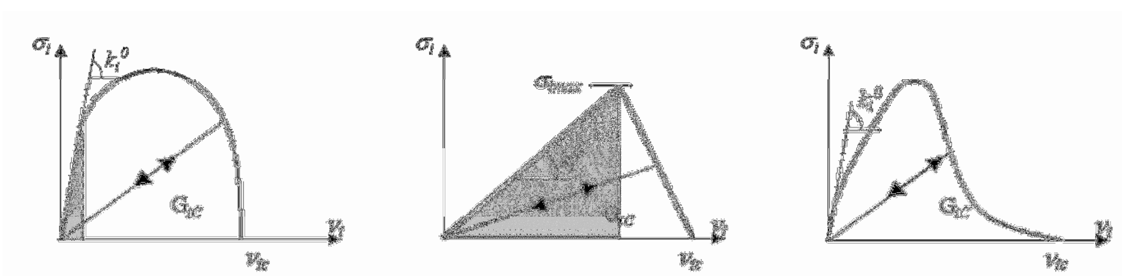


Figure 2: Cohesive laws for the interfaces

According to fracture mechanics considerations an important parameter of the model is surely the fracture toughness G_{ic}, i.e. the area under the curves of Figure 2. Contrary to the fracture mechanics approach like VCE (Virtual Crack Extension method) or VCCT (Virtual Crack Closure Technique), cohesive elements can be used with a coarser mesh at the crack front location [1,7]. According to [1], at least three finite elements must be active in the process zone, which is the zone where intermediate damage takes place.

2.2 Identification procedure for the inter-laminar damage mode

In this paper, the bi-triangular cohesive law of Figure 2 is used. The different parameters that must be identified are the fracture toughness G_{Ic} and G_{IIc}, assuming that $G_{IIIc} = G_{IIIc}$; the initial stiffness k_I^0 and k_{II}^0, assuming that $k_{III}^0 = k_{II}^0$; the interface strengths σ_{33}^{max} and τ_{13}^{max}, assuming that $\tau_{23}^{max} = \tau_{13}^{max}$. In the material model, it is considered that the elastic energy of the interface represented by the grey triangle in Figure 2 is identical for modes I and II. It results that the inter-laminar shear strength is not independent and is given by:

$$\tau_{13}^{\max} = \sigma_{33}^{\max} \sqrt{\frac{G_{IIC} k_{II}^{0}}{G_{IC} k_{I}^{0}}}$$

In practice, only 0°/0° interfaces are studied, and the tested specimens are of the $[0]_n$ type. The different parameters listed previously are identified by fitting simulation to experimental results. Typically, DCB and ENF tests are conducted (Figures 3 and 4). It should be noted that the interface stiffness values are somehow artificial: they must take a high value, knowing that in a perfect interface they must be infinite. In the finite elements practice however, the smallest possible value should be preferred in order to avoid working with a too fine mesh while keeping anyway a good representation of the real physical behavior. Typical solid finite element models for DCB and ENF are illustrated in Figure 5.

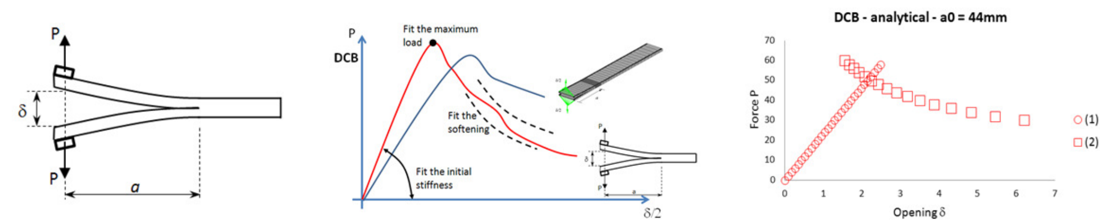


Figure 3: DCB, fitting scheme and analytical solution for a unidirectional laminate

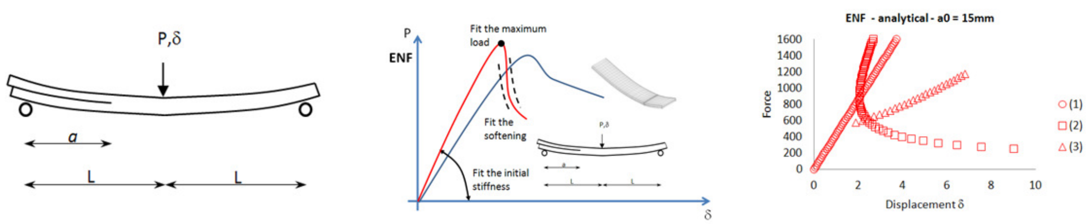
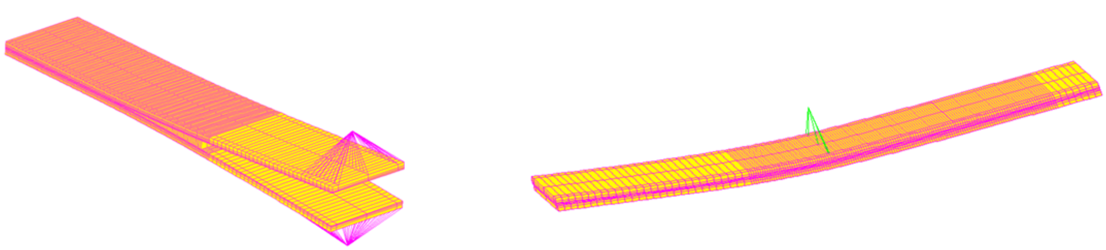


Figure 4: ENF, fitting scheme and analytical solution for a unidirectional laminate



DCB model ENF model

Figure 5: DCB and ENF finite element models

In Figure 6, the simulation results obtained with SAMCEF are compared to the physical tests on coupons. A $[0]_{16}$ laminate made up of UD plies is considered. The test results are given by the thin lines, while the analytical solution based on the beam theory is illustrated by the red circles. SAMCEF results are given by the black spots. The fitting procedure allows identifying the value of the material model parameters. It is noted that even the value of the fracture toughness G_{IC} and G_{IIC} are a little bit modified from the test results in order to perfectly fit the part of the reaction-displacement curve corresponding to the crack propagation.

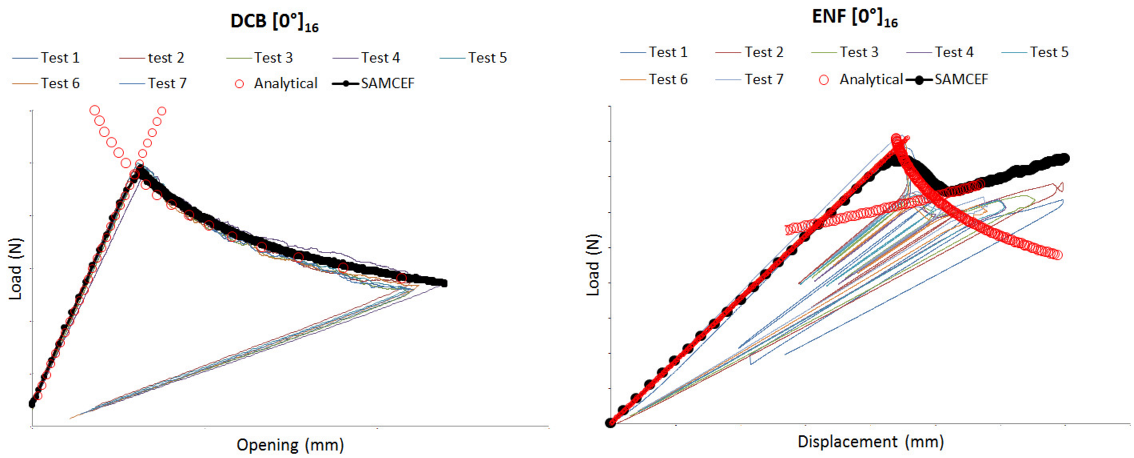


Figure 6: DCB and ENF: comparison between SAMCEF and tests results

2.3 Validation for $[0]_n$ laminates

Usually the MMB test is used to identify the coupling between mode I and mode II. Here, we assume that α=1, and MMB allows to validate the value of the parameters identified based on DCB and ENF as explained previously in Figure 6. The comparison between simulation and tests for MMB is given in Figure 7 for the 0°/0° interface. The good agreement between tests and simulation validates the value of the parameters.

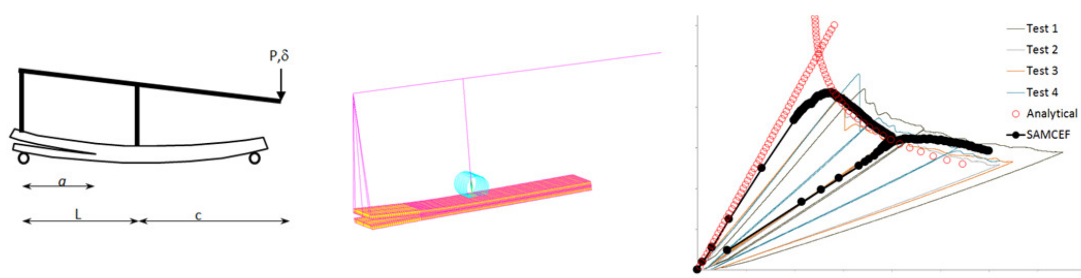


Figure 7: MMB: comparison between SAMCEF and tests results

As demonstrated in what follows, when ENF specimens with θ°/-θ° interfaces are considered, damage inside the plies may also appear during the crack propagation [16]. An intra-laminar damage model must therefore be used and so should be available in the finite element code and used together with the inter-laminar damage model.

3 INTRA-LAMINAR DAMAGE MODELING

Although delamination is certainly the most frequent mode of failure in laminated composites, in practical applications it is necessary to consider the ply degradation as well. Besides the classical failure criteria such as Tsai-Hill, Tsai-Wu and Hashin, an advanced intra-laminar damage model is available in SAMCEF. This progressive ply damage model relies on the development proposed in Ladeveze and LeDantec [15]. For intra-laminar damage, the potential in (3) with damage (here in plane stress) is used, where d_{11}, d_{22} and d_{12} are the damages related to the fibers, the transverse and the shear directions, respectively. These damage variables allow considering damage associated to the fiber direction, cracks in the transverse direction and de-cohesion between fibers and matrix. The thermodynamic forces are derived from this potential and manage the evolution of the damages via relations of the form $d_{11} = g_{11}(Y_{11})$, $d_{22} = g_{22}(Y_{12}, Y_{22})$ and $d_{12} = g_{12}(Y_{12}, Y_{22})$. A delay effect can also be defined, seeing as a time regularization technique, in order to smooth the occurrence of the damages. Moreover, non-linearities are introduced in the fiber direction, in traction and compression.

$$e_d = \frac{\sigma_{11}^2}{2(1-d_{11})E_1^0} - \frac{\nu_{12}^0}{E_1^0}\sigma_{11}\sigma_{22} - \frac{\langle\sigma_{22}\rangle_+^2}{2(1-d_{22})E_2^0} + \frac{\langle\sigma_{22}\rangle_-^2}{2E_2^0} + \frac{\sigma_{12}^2}{2(1-d_{12})G_{12}^0} \tag{3}$$

Finally the model can be coupled to plasticity with isotropic hardening. The non-linear behaviors taken into account in this model are illustrated in Figure 8: non linearity in the fiber direction and non-linearity including plasticity in the matrix. The parameter identification procedure is discussed in [15,17].

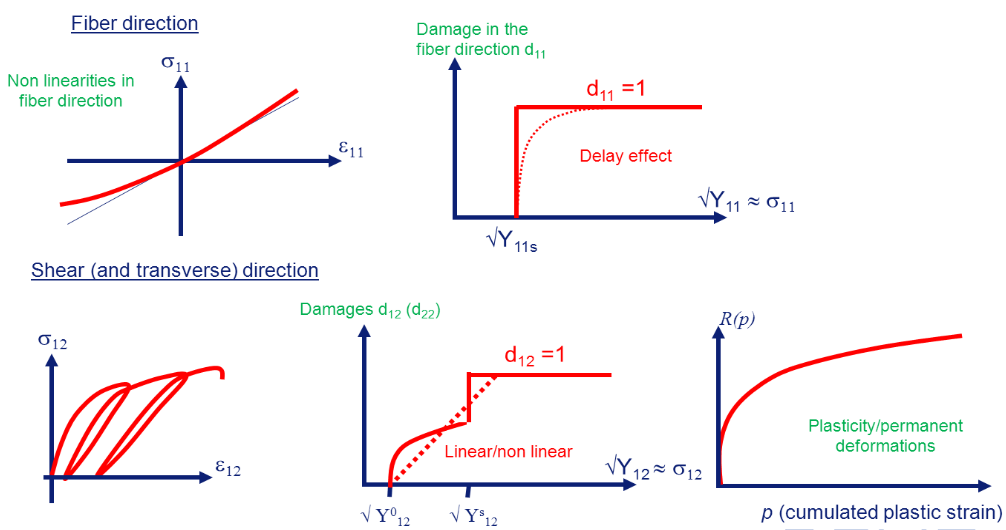


Figure 8: Non-linearities in the damage model for the UD ply

4 VALIDATION AT THE COUPON LEVEL

Besides the identification and validation conducted for 0°/0° interfaces as described in Figures 3 to 7, θ°/-θ° interfaces are also studied in order to show that, in some general cases, it is important to model not only the damage at the interface of the plies, but also the damage inside the plies. This is illustrated for the ENF test case, as depicted in Figure 9, where simulation is compared to analytical solutions and to test results. It was observed in Figure 6 that for a $[0]_n$ laminate the behavior is quasi-linear up to the crack propagation load, which is the maximum point of the reaction-displacement curve. However, when the laminate includes ±45° orientations, the non-linear behavior observed in the tests can only be reproduced when the damage inside the plies is modeled. Doing so, we note a very good agreement between tests (light lines) and simulation (dark spots). For DCB, damage inside the ply is not observed.

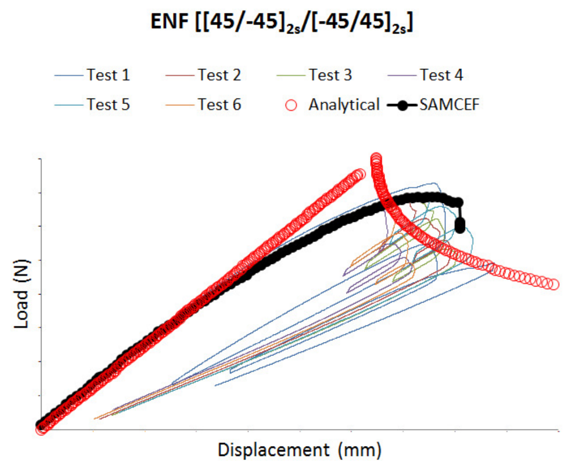


Figure 9: DCB and ENF for θ°/-θ° interfaces

5 CONCLUSIONS

A solution procedure to solve delamination problems at the coupon level with the SAMCEF commercial finite element software has been presented. Laminated composites made up of unidirectional plies have been studied. A cohesive elements approach has been used. The parameter identification procedure for the inter-laminar damage model has been discussed. Good agreements between tests and simulation results have been obtained for 0°/0° interfaces. For general interfaces including θ°/-θ° orientations, with θ different from 0, it was shown that the intra-laminar damage (that is damage inside the plies) must also be taken into account in the model in order to reproduce the full non-linear behavior observed in the tests.

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