

DAMAGE MODELING OF LAMINATED COMPOSITES: VALIDATION OF THE INTRA_LAMINAR LAW OF SAMCEF AT THE COUPON LEVEL FOR UD PLYS

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Abstract

In this paper, the material model available in SAMCEF for the progressive ply damage modeling of composite laminates is validated by comparing simulation and tests results, at the coupon level. Laminated composites with unidirectional plies (UD) of different orientations are studied. The parameter identification procedure is discussed. It is shown that a very limited amount of tests is needed to identify the parameters, and that once obtained, these can be used in the simulation to predict the behavior of coupons made of any other stacking sequence.

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 plies forming the laminated composite structure. Although delamination is a very important mode of failure [1,2], intra-laminar failure modes can't be ignored. They are studied in this paper, and progressive damages impacting matrix cracking, fibers breaking, and de-cohesion between fibers and matrix are considered. Even if lots of models are available in the literature [3-8], the formulation developed in SAMCEF for modeling the damages inside the unidirectional plies of a laminate is based on the continuum damage mechanics approach initially developed in [9], in which the laminate is made of homogenous plies (of various orientations) 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 progressive damage model compared to some others is that a parameter identification procedure can be developed. This procedure is based on test results at the coupon level, and allows determining not only the elastic properties but also the value of the parameters describing the non-linear behavior of the material. Moreover, the model is native in SAMCEF and there is no need for additional (not free) plug-ins to solve the progressive damage problem. In this paper, the damage model is first presented, and then the parameter identification procedure is discussed. The procedure is validated with a comparison between test and simulation results from a coupon with a stacking sequence that was not used for the

identification. To be complete, information on modeling delamination with SAMCEF (inter-laminar failure) can be found in [10]. Once obtained at the coupon level, the damage models (for inter and intra-laminar damages) can be used at the upper stages of the pyramid [11] in order to determine the non-linear progressive damage behavior of larger components as classically done in aeronautics applications (Figure 1), where now predictive simulations are the companions of physical tests. Quasi-static tests are considered in this paper.

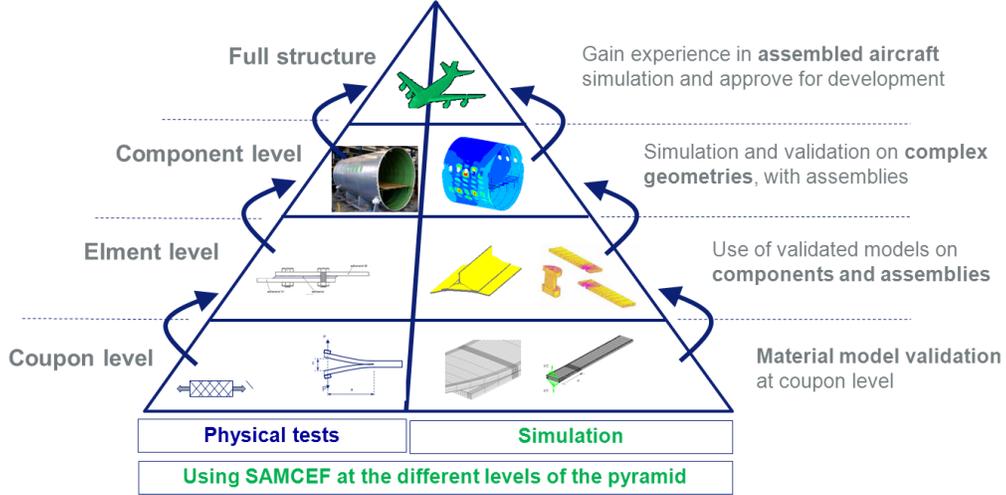


Figure 1. The pyramid of tests, divided in physical and virtual testing at each stage

2. Progressive damage analysis

2.1. 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 [9]. For intra-laminar damage, the potential with damage (here in plane stress) in (3), written in the orthotropy coordinate system, is used, where d_{11} , d_{22} and d_{12} are the damages related to the fibers, the transverse and the shear directions, respectively.

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

These damage variables allow considering damage associated to the fiber direction, cracks in the transverse direction and de-cohesion between fibers and matrix (Figure 2). The thermodynamic forces represent the effect of the loading in the corresponding mode. These thermodynamic forces are derived from the 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 $d_{12} = g_{12}(Y_{12}, Y_{22})$. For instance, the thermodynamic force associated to shear is given in (2).

$$Y_{12} = \frac{\sigma_{12}^2}{2(1-d_{12})^2 G_{12}^0} \quad (2)$$

In Figure 3, it is seen that for a laminate submitted to pure shear (σ_{12}, γ_{12}), a decrease in the stiffness is observed after some loading/unloading scenarios of increased amplitude, reflecting that damage occurs in the matrix. Moreover, unloading reveals the existence of permanent deformation, which is taken into account via a plasticity model. On top of that, non-linearities are introduced in the fiber direction, in traction and compression. It is noted from equation (1) that in the transverse direction, only traction leads to damage, but not compression, assuming the unilateral action of damage in direction 2 (cracks closure in the matrix in compression). These behaviors result from the tests interpretation [9].

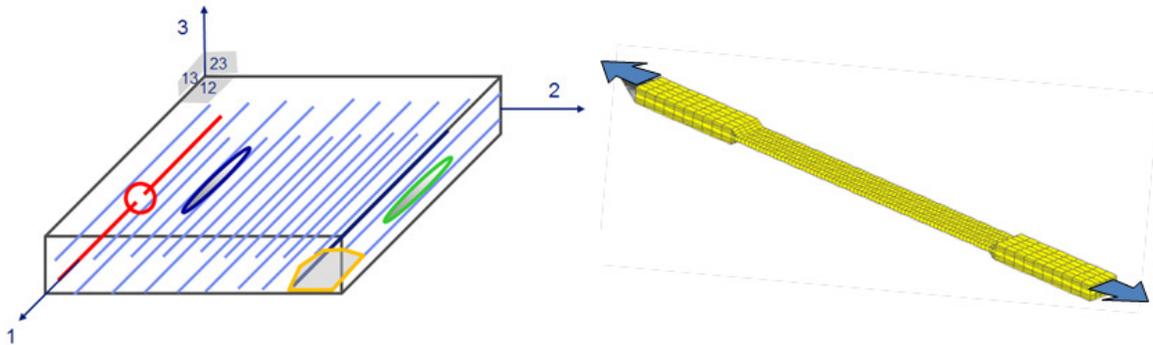


Figure 2. Possible damages in a UD ply, impacting fiber failure, matrix cracking and de-cohesion between fibers and matrix; model of the coupon

The non-linear behaviors taken into account in this model are summed up in Figure 3: they include non-linearity in the fiber direction and non-linearity including plasticity in the matrix. A delay effect can also be defined, seeing as a time regularization technique, in order to smooth the occurrence of the damages and avoid numerical issues.

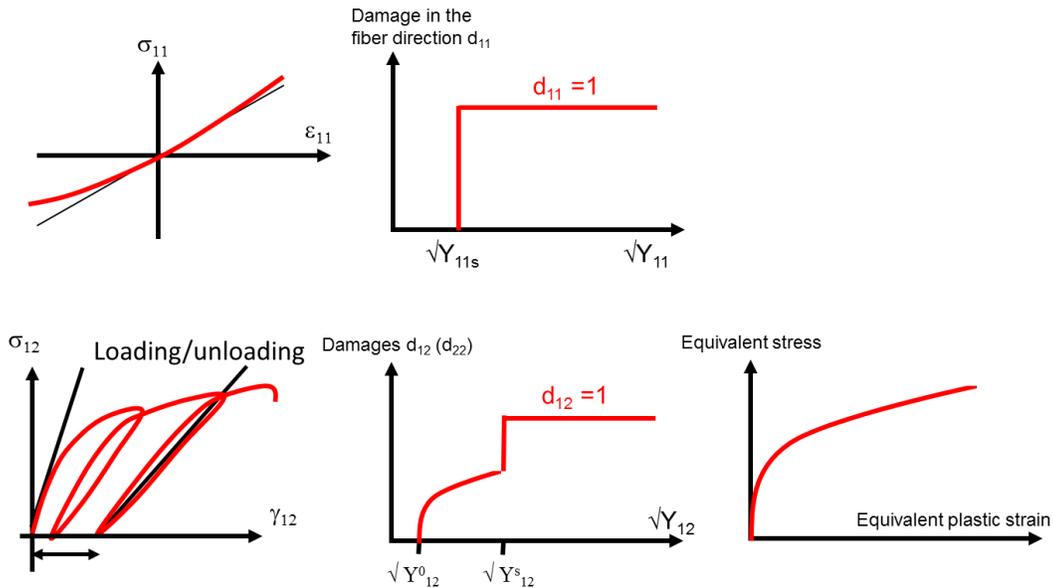


Figure 3. Non-linearities and damage evolution in the progressive damage model for UD plies

2.2. Identification procedure

From the coupon testing conducted on standard machines according to some standards like ASTM and equipped with strain gauges, the longitudinal stress σ_L and the axial and transversal strains (ϵ_L and ϵ_T) are obtained. Based on this information, the material behavior in each ply can be determined. Four series of tests are done, each one on a specific stacking sequence and/or loading scenario. As 5 successful tests are usually required, it means that 20 successful tests must be conducted to cover the 4 series. This is enough to identify the parameters of the progressive damage ply model and the classical elastic properties. The identification procedure is done without extensive use of simulation. It is rather a procedure based on EXCEL sheets, which can be speed up by using some very simple FORTRAN programming. Simulation is used to validate the identified values. The required stacking sequences mentioned above are not arbitrary; they are instead well defined, in order to be able to identify the whole set of elastic properties, evolution of the damage and of the non-linearities of the material. One of these specific stacking sequences is made of plies at $\pm 45^\circ$. The loading scenario are either classical, meaning that the coupon is loaded up to the final failure, or it is based on the loading/unloading (cyclic) sequences as described in Figure 3. As an example, in Figure 4, a $[\pm 45]_{2s}$ laminate is studied. Based on the tests results as given in Figure 5, the evolution of the damage variable d_{12} is plotted as a function of the equivalent thermodynamic force Y_{12} . The hardening law of the plastic model is also identified. This allows determining the curves of Figure 3, which then feed the material model of SAMCEF. In Figure 5, it is checked that the results obtained with SAMCEF are in a very good agreement with the test results, not only for the global non-linear behavior, but also for the failure load estimation, the damage evolution (stiffness decrease measured during unloading) and the permanent deformation (plasticity). It is clear from Figure 5 that plasticity can't be neglected when studying polymer matrix composites. The non-linearities appearing during loading/unloading, which is certainly due to friction between fibers and matrix, are not taken into account in the model. Our experience is that it doesn't influence the results.

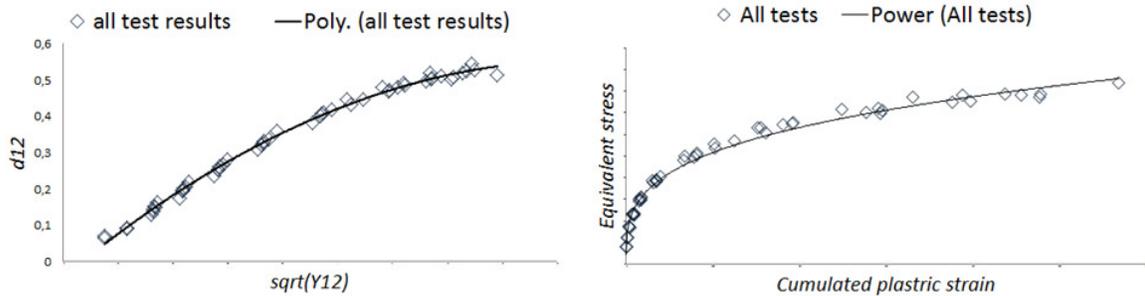


Figure 4. Non-linearities and damage evolution in the progressive damage model for UD plies

A specific angle ply laminate is considered to identify the material behavior in the transverse direction, which is actually coupled to shear. In order to take into account the coupling between shear and transverse effects, an equivalent thermodynamic force Y is used (3), and the evolution of d_{22} is, moreover, proportional to d_{12} :

$$Y = Y_{12} + bY_{22} \quad \text{and} \quad d_{22} = cd_{12} \quad (3)$$

The material behavior in the pure transverse direction is also identified, as illustrated in Figure 6. The resulting damage laws evolutions are also given in Figure 6. This information feeds the progressive damage ply model of SAMCEF.

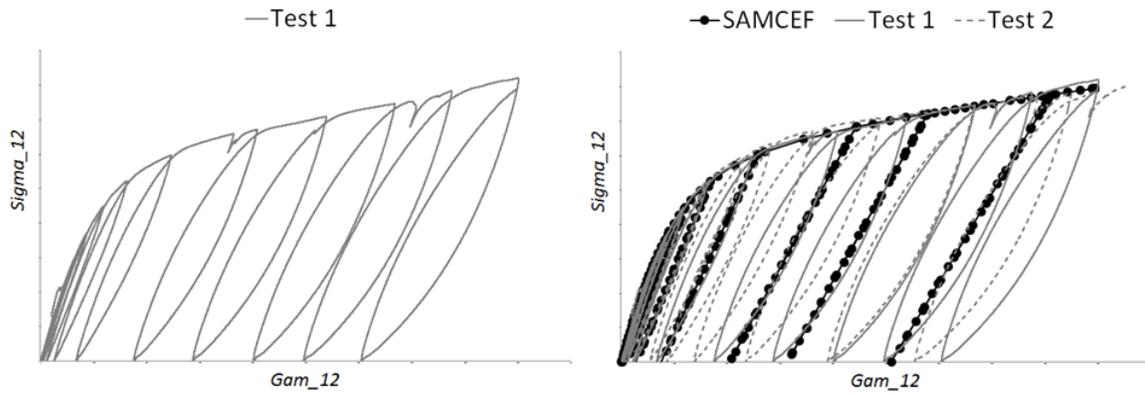


Figure 5. Non-linearities and damage evolution in the progressive damage model for UD plies

In Figure 7, the evolution of the stiffness modulus E_{11} in the fiber direction is identified, in traction (hardening effect) and compression (softening effect), as illustrated in Figure 3. The softening effect appearing in compression is (partly) due to fiber micro-buckling. The (very small) hardening effect in traction is related to the alignment of the fibers in the loading direction. The failure loads in the fiber direction are also easily determined based on the tests, in traction and in compression.

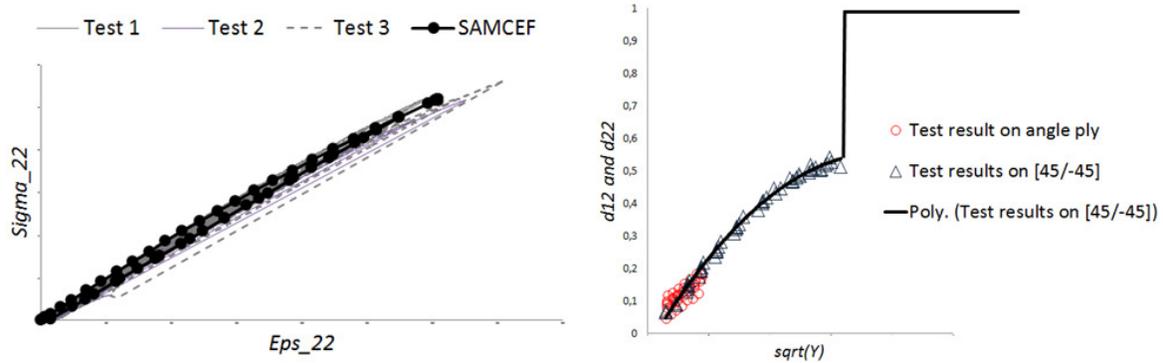


Figure 6. Identification of the material behavior in the transverse direction. Evolution of d_{12} and d_{22} as a function of the equivalent thermodynamic force Y

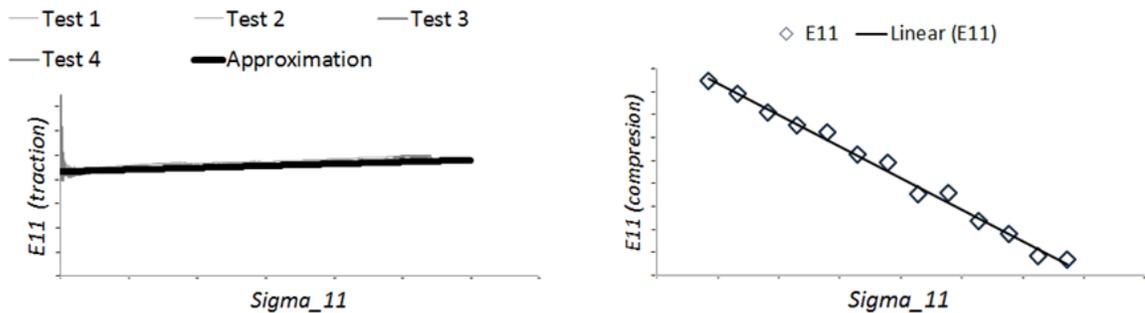


Figure 7. Evolution of E_{11} in traction and compression

In Figure 8, the force F_L and the corresponding longitudinal strain in the coupon are plotted. This allows determining the strength in the fiber direction. In this case, the force is applied on the coupon in the model, and the displacement becomes very large when the maximum load has been reached.

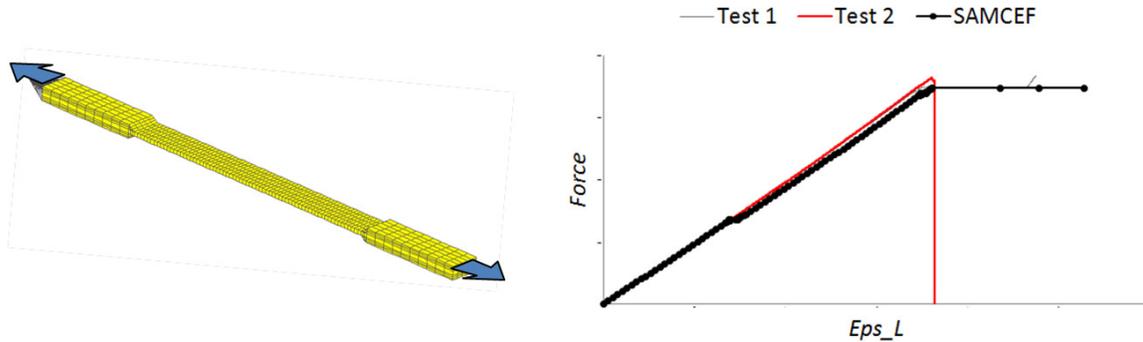


Figure 8. Load-longitudinal strain diagram for the failure in the fiber direction

From Figure 9, it is clear that when inaccurate values of the parameters are used in the progressive ply damage model, simulation results are not in a good agreement at all with the tests. In Figure 9, the damage and plasticity laws of Figure 4 were modified, as well as the failure load. This solution should be compared to the one obtained in Figure 5. It is then evident that an accurate identification procedure is necessary.

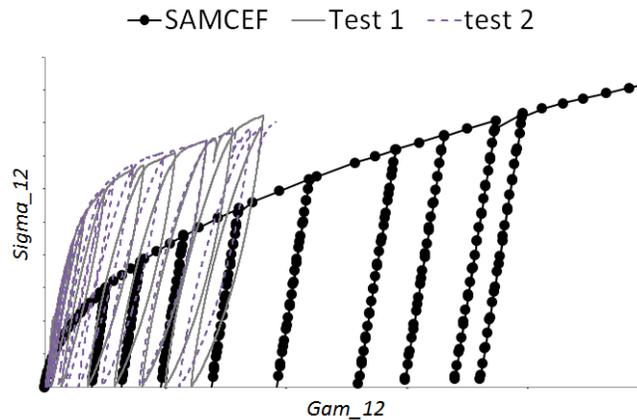


Figure 9. Comparison between tests and simulation when inaccurate values of the parameters are used

3. Validation

In order to validate the value of the parameters of the progressive damage model, a blind test is conducted on a $[67.5/22.5]_{2s}$ coupon. This stacking sequence was not used for the parameter identification. Simulation is run, and then the comparison to test results is done. A very good agreement is obtained, as illustrated in Figure 9. Compared to the initially identified value of the parameters, just the failure load in the transverse direction had to be a little bit increased. The value of the progressive ply damage model are then validated, and can be used to study any coupon made of an arbitrary number of plies and arbitrary orientations. The only restrictions are that the base material properties (of the fibers and the matrix) and the fiber volume fraction can't be changed, and that the properties are obtained for given temperature and humidity levels.

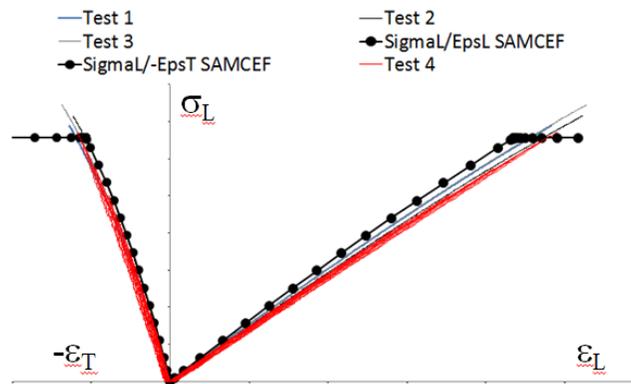


Figure 9. Validation of the values of the progressive ply damage model parameters on a $[67.5/22.5]_{2s}$ laminate

4. Conclusions

In this paper, the composite material model available in SAMCEF for the progressive ply damage modeling of laminates has been validated by comparing simulation and tests results, at the coupon level. Laminated composites with unidirectional plies of different orientations have been studied. The parameter identification procedure has been discussed. It has been shown that a very limited amount of tests is needed to identify the parameters, and that once obtained, these can be used in the simulation to predict the behavior of coupons made of any other stacking sequence. A validation has been done on a laminate made up of a stacking sequence not used for the identification. Thanks to the identification procedure, the values of the progressive ply damage model are then available to study any coupon made of an arbitrary number of plies and arbitrary orientations, and to address damage analysis at the upper stages of the pyramid of tests.

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