

# IMPACT ON LAMINATED COMPOSITE PLATES: COMPARISON OF TEST AND SIMULATION RESULTS OBTAINED WITH LMS SAMTECH SAMCEF

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**Summary:** *In this paper, the material models available in LMS Samtech Samcef for inter and intra-laminar damage of laminates made up of UD or woven fabric plies, are presented. They are based on the work of Ladevèze, Allix and Hochard, and rely on continuum damage mechanics. For inter-laminar damage (delamination), the cohesive elements approach is used. The models are briefly recalled, together with their parameter identification procedure at the coupon level. They are then used to simulate the low energy impact on a plate. Good agreement between tests and simulation demonstrate that the numerical solution can be a reliable companion of the physical tests.*

## 1 INTRODUCTION

Even if lots of models and analysis approaches exist in the literature to study damage of composites, the solution described in this paper relies on the work of Ladevèze, Allix and Hochard [1-3], in the frame of the finite elements method. For inter-laminar damage, the cohesive elements are used. Both intra- and inter-laminar damage models are based on the continuum damage mechanics. Specific identification procedures are derived to determine the value of the parameters at the coupon level of the pyramid of tests (Figure 1). Once obtained, these values are used in models at the upper stages of the pyramid, where simulation, as a virtual twin, becomes a companion of the physical tests.

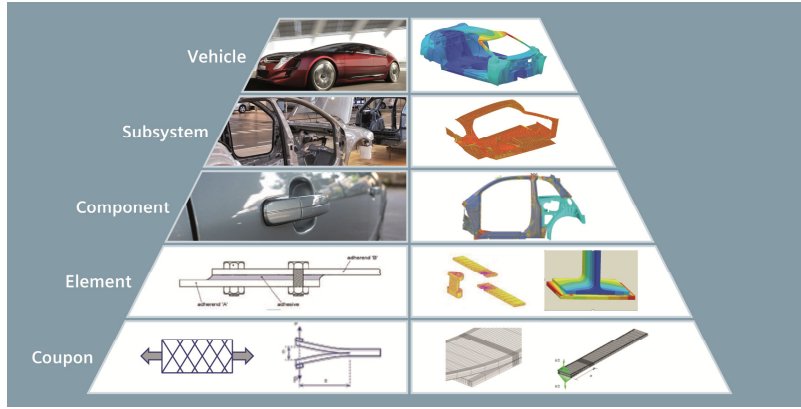


Figure 1: The pyramid of tests: physical and predictive virtual prototypes

## 2 INTRA-LAMINAR DAMAGE MODELS

### 2.1 Damage model for the unidirectional (UD) plies

The model is described in details in [1]. Damage variables are introduced in the energy density and the potential (1), written here for the plane stress state, is used.

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

The model includes 23 parameters (to be identified): the 9 elastic orthotropic properties in 3D ( $E_1^0, E_2^0, E_3^0, \nu_{12}, \nu_{23}, \nu_{13}, G_{12}^0, G_{13}^0, G_{23}^0$ ) and specific parameters associated to damage and plasticity (like  $Y_{11s}, Y_{012}, Y_{s12}, R_0, \beta$  and  $n$  in Figures 2 and 3). The so-called thermodynamic forces  $Y_i$  (see reference [1]) are the derivatives of the potential  $e_d$  with respect to the damage variables  $d_i$ . The evolution of the different damage variables with respect to the corresponding thermodynamic force is given in Figure 1. The two damages in the matrix  $d_{12}$  and  $d_{22}$  are coupled and  $d_{22}$  behaves like  $d_{12}$  (with a different magnitude). The damage in the transverse direction appears only in tension, not in compression, as cracks get closed in the matrix under a compressive loading (see eq. (1)).

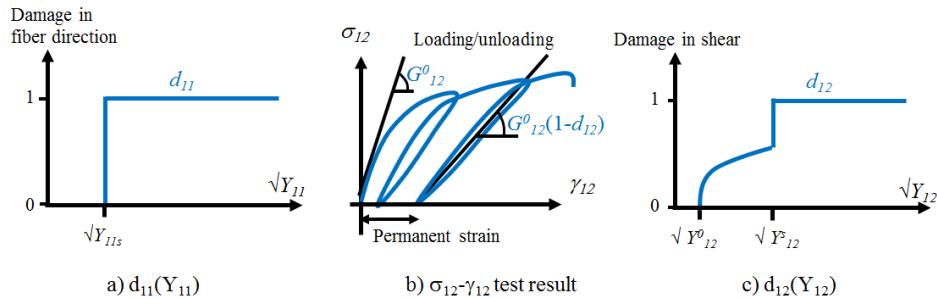


Figure 2: Damages in the fiber direction (left) and in the matrix

Besides damage, non-linearity is also taken into account in the fiber direction (Figure 3a). For the matrix, inelastic effects are considered in the form of a plastic law, which captures the

permanent deformations (Figures 2 and 3). These material behaviors come from the tests interpretation.

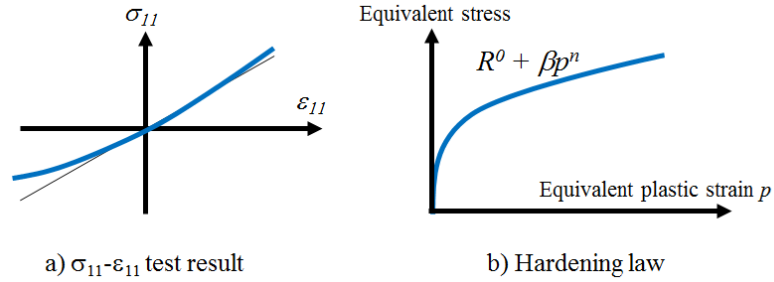


Figure 3: Non linearity in the model

Advanced damage models [4] are also available in LMS Samtech Samcef, but are not described here.

## 2.2 Damage model for the woven fabric (WF) plies

The damage model for the balanced woven ply is described in [2]. Here again, a potential including the damage variables is written (2). Now,  $d_{11}$  and  $d_{22}$  correspond to the damage in the weft and wrap directions, as fibers are now also present in the transverse direction.

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

The behaviors illustrated in Figures 2 and 3 are still valid, except that  $d_{22}$  now behaves like  $d_{11}$ .

## 2.3 Numerical solution

Regularization techniques in space [5] and time [6] can be used in LMS Samtech Samcef in order to avoid problems linked to the localization of the damage.

## 3 INTER-LAMINAR DAMAGE MODEL

The inter-laminar damage model for delamination is based on the cohesive elements approach [3]. A potential is assigned to the interface elements, and three damage variables  $d_i$  are related to modes *I*, *II* and *III* (opening, sliding and tearing modes, respectively).

$$e_d = \frac{1}{2} \left[ k_I^0 \langle \varepsilon_{33} \rangle_-^2 + k_I^0 (1-d_I) \langle \varepsilon_{33} \rangle_+^2 + k_{II}^0 (1-d_{II}) \gamma_{31}^2 + k_{III}^0 (1-d_{III}) \gamma_{32}^2 \right] \quad (3)$$

$k_i^0$  in (3) is the undamaged stiffness. Thermodynamic forces  $Y_i$  are obtained by deriving (2) with respect to  $d_i$ . For mixed mode loading, the damage evolution is related to the inter-laminar fracture toughness ( $G_{IC}$ ,  $G_{IIC}$  and  $G_{IIIC}$ ) in an equivalent thermodynamic force  $Y$  taking the following form:

$$Y = \sup_{\tau \leq t} G_{IC} \left\{ \left( \frac{Y_I}{G_{IC}} \right)^\alpha + \left( \frac{Y_{II}}{G_{IIC}} \right)^\alpha + \left( \frac{Y_{III}}{G_{IIIC}} \right)^\alpha \right\}^{1/\alpha} \quad (3)$$

$\alpha$  in (4) is a coupling coefficient, and  $t$  represents the time (pseudo-time when static analysis is addressed). The three damage variables  $d_i$  have the same evolution over the loading and a unique damage  $d$  is therefore defined. The damage is related to  $Y$  via a function  $g(Y)$ . Three different functions  $g(Y)$  are available leading to polynomial, bi-triangular and exponential cohesive laws. This model can be used when the plies are unidirectional or woven fabrics.

## 4 PARAMATER IDENTIFICATION AND RESULTS ATE THE COUPON LEVEL

### 4.1 Identification for the UD damage model

Standard testing (e.g. ASTM D3039, [www.astm.org](http://www.astm.org)) is performed to obtain the longitudinal stress  $\sigma_L$  and the axial and transversal strains ( $\epsilon_L$  and  $\epsilon_T$ , respectively). Based on this stress/strain output at the coupon level, the 23 parameters of the ply model are determined. In practice, four series of tests are conducted, each series on a specific (well-defined) stacking sequence and/or loading scenario. As typically 5 successful tests are usually required, it results that 20 (= 4 x 5) successful tests must be conducted to cover the 4 series, that is a total of 20 tested coupons. This is enough to identify the 23 parameters of the progressive damage ply model, i.e. the damage, plastic and initial elastic properties. The identification procedure is done without extensive use of simulation. It is a simple procedure based on EXCEL sheets, which can be sped up by some very simple programming. A comparison between an ASTM D3039 test and simulation [7] is used to validate the identified values on a stacking sequence not used for the identification (Figure 4).

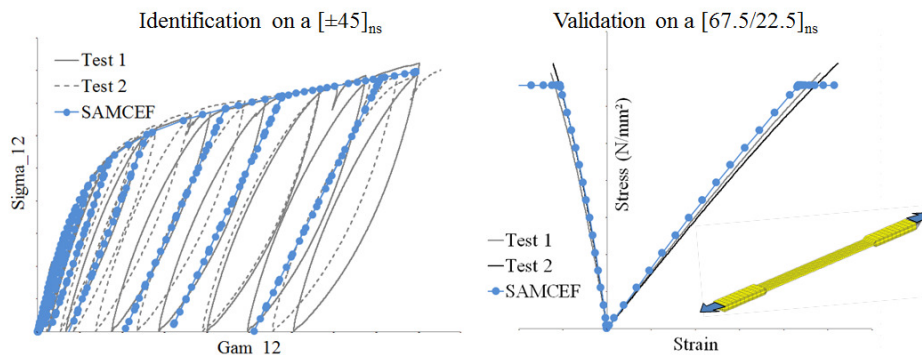


Figure 4: Comparison between test and simulation for the identification and validation at the coupon level for laminates made of UD plies (intra-laminar damage model)

### 4.2 Identification for the WF damage model

For the woven fabric damage model, an approach very similar to the one used for the unidirectional plies is explained in [2] and applied in [8]. Results are provided in Figure 5.

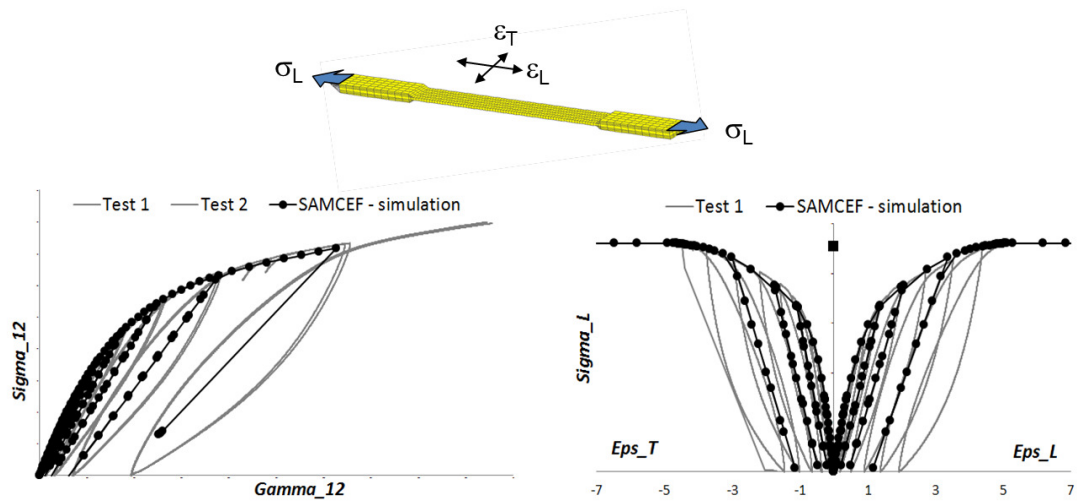


Figure 5: Left: identification on a  $[45]_n$ ; right: validation on a  $[67.5]_n$

### 4.3 Identification for the inter-laminar damage model

For the cohesive model, specific DCB, ENF and MMB tests ([www.astm.org](http://www.astm.org)) are performed. Finite element models are developed and a fitting between experiments and numerical results is conducted (Figure 6) to get the value of the parameters. Analytical solutions based on the beam theory are also used to fine tune these values.

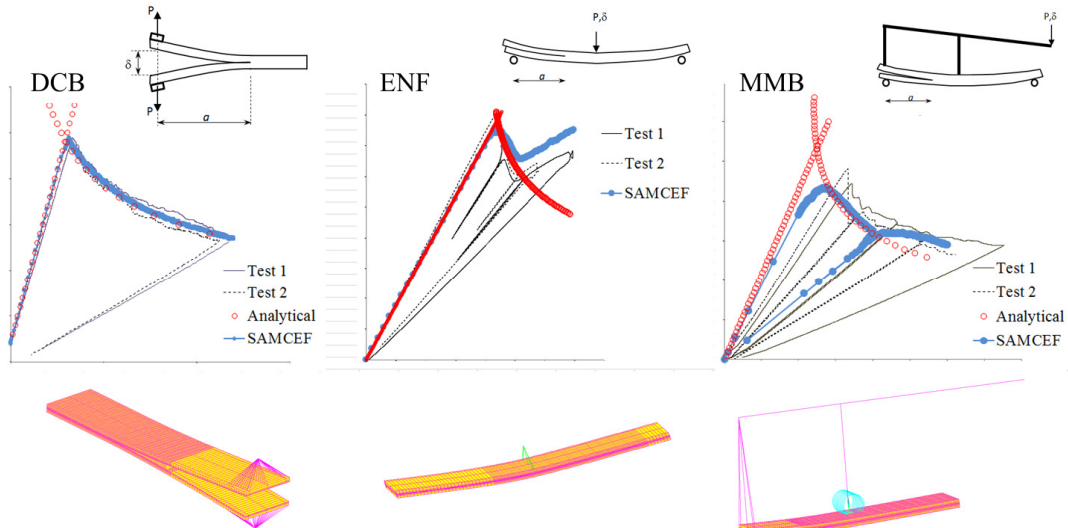


Figure 6: Comparison between test and simulation for the identification of the inter-laminar damage model parameters at the coupon level (delamination)

Results for laminates made up of woven fabric plies are provided in Figure 7. Oscillations appear during the tests, and are due to the weaving pattern, but this effect cannot be reproduced with the current model.

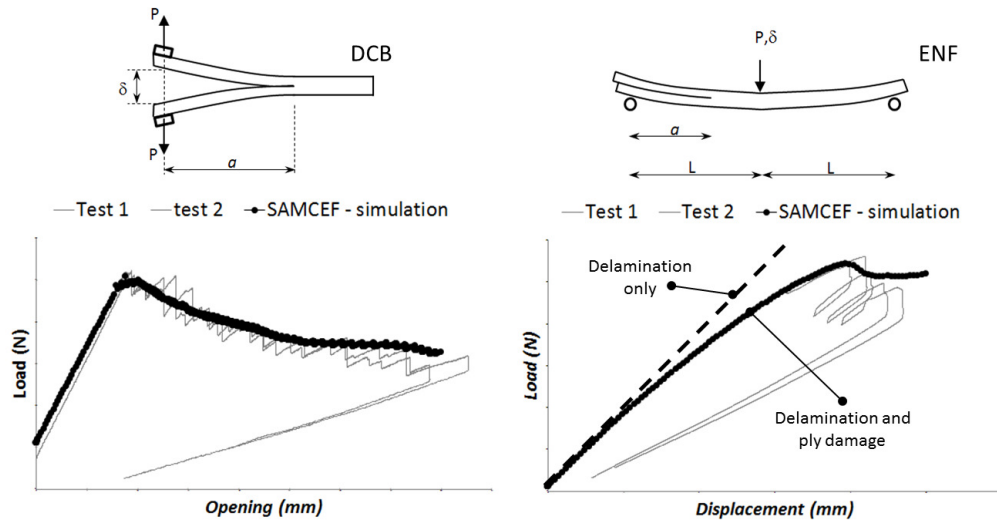


Figure 7: Left: DCB problem with 45° interfaces; right: ENF problem with 45° interfaces

## 7 RESULTS FOR THE IMPACTED PLATES

The previously identified parameters of the inter- and intra-laminar damage models are now used in simulations at the upper stage of the pyramid of Figure 1. Solid shell finite elements with EAS (Enhanced Assumed Strain) and ANS (Assumed Natural Strain) formulations are used. The element height is equal to the ply thickness. Interface elements are defined between each ply.

### 3.1 Plate made of unidirectional plies

In a first application, a  $[45/0/-45/90]_s$  plate is submitted to an impact. Test results are obtained with a C-scan. The simulation determines the amount of damage in each interface; red meaning completely broken while blue corresponds to no local damage. The damaged interfaces are illustrated in Figure 8. The agreement between test and simulation is very good.

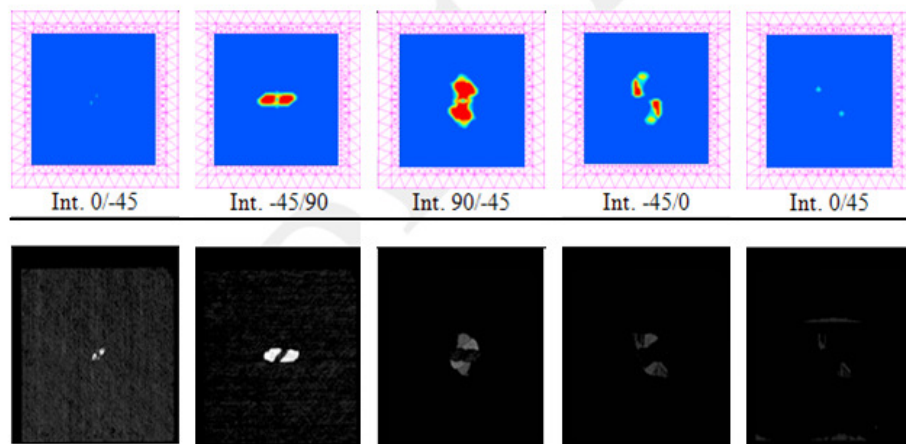


Figure 8: Results of the impact on the laminated plate made of UD plies

### 3.2 Plate made of woven fabric plies

In the second application, a  $[\pm 45/0]_{3s}$  plate is submitted to an impact. Test results are obtained with a C-scan. Seeing the large thickness of the plate, damage detections with C-scan are conducted twice: first from the top (“FRONT” in Figure 9), then from the bottom (“BACK”) of the laminate. The agreement between test and simulation is very good.

Comparing the results for woven fabric of Figure 9 to the results for unidirectional plies of Figure 8, it is clear that the damage patterns are very different. This difference can be captured by simulation.

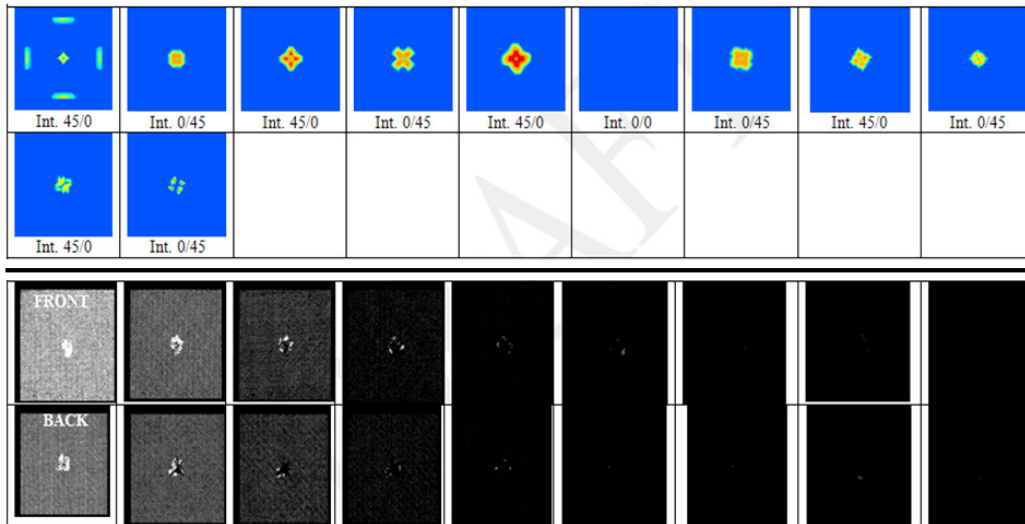


Figure 9: Results of the impact on the laminated plate made of WG plies

## 9 CONCLUSIONS

In this paper, we have described the damage models for laminates made up of UD and WF plies available in the LMS Samtech Samcef finite element software. Both inter and intra-laminar damages are addressed. The formulations and the methodology were presented and the parameter identification procedure at the coupon level was explained. Very good agreements were found between tests and predictive simulations at the coupon level and at the upper stages of the pyramid for the specific case of impacted plates.

## REFERENCES

- [1] P. Ladeveze and S. Le Dantec (1992). Damage modeling of the elementary ply for laminated composites, *Composites Science and Technology*, **43**, 123-134.
- [2] C. Hochard, P.A. Aubourg and J.P. Charles (2001). Modelling of the mechanical behavior of woven fabric CFRP laminates up to failure. *Composites Science and Technology*, **61**, 221-230.
- [3] O. Allix and P. Ladevèze (1992). Interlaminar interface modelling for the prediction of laminate delamination, *Composite Structures*, **22**, 235-242.
- [4] F. Daghia, P. Ladevèze, F. Bordeu and C. petiot (2009). Sur la validation d’un mésomodèle base sur la micromécanique pour le calcul à la rupture des composites stratifiés. JNC 16, Toulouse, France.

- [5] N. Germain (2006). Modélisation non locale de l'endommagement dans les structures composites. PhD Thesis, Ecole Nationale Supérieure des Mines de Paris.
- [6] O. Allix, P. Feissel and P. Thévenet (2003). A delay damage mesomodel of laminates under dynamic loading: basic aspects and identification issues. *Computers & Structures*, 81, pp. 1177-1191.
- [7] M. Bruyneel, T. Naito and Y. Urushiyama (2014). Validation of material models for inter and intra-laminar damage in laminated composites, 2014 ASC 29/US-Japan 16 ASTM D30 Conference, UC, San Diego, USA.
- [8] M. Bruyneel, J.P. Delsemme, A.C. Goupil, P. Jetteur, C. Lequesne, T. Naito and Y. Urushiyama (2014). Damage modeling of woven fabric laminates with SAMCEF: validation at the coupon level. *Advanced Computational Methods in engineering Conference – ACOMEN*, Ghent, Belgium, 23-28 June, 2014.