INDUSTRIAL VALIDATION OF PROGRESSIVE DAMAGE MODELS FOR LAMINATED COMPOSITE MATERIALS AND STRUCTURES: AUTOMOTIVE APPLICATIONS

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1. Introduction

In order to propose predictive simulation tools for composites, material models able to represent the different modes of degradation of the plies forming the laminate must be used. Delamination must also be taken into account in the problem. Both inter and intra-laminar damages in laminated composites are considered here. Material models relying on a simple and consistent parameter identification procedure at the coupon level are described. These models are fully implemented in the SAMCEF finite element code. Simulation is compared to experimental results, and validations are done at the coupon level and at upper stages of the pyramid of tests.

The material model for the intra-laminar damage is based on the continuum damage mechanics. In each ply, damage variables impacting the stiffness are associated to the different failure modes, representing the fibre breaking, matrix cracking and de-cohesion between fibres and matrix. The specific damage model is first presented as well as the parameter identification procedure. This procedure relies on a very limited number of tests at the coupon level. The obtained parameter values are then validated on a coupon with a stacking sequence not used for the identification.

The cohesive elements approach is used for modelling inter-laminar damages. A damage model is assigned to some interface elements to represent the possible delamination and a fracture criterion is used to decide on the inter-laminar crack propagation. Using such cohesive elements in the analysis allows estimating the propagation load and predicts the crack propagation and the residual stiffness and strength during the progressive fracture. The inter-laminar damage model and the parameter identification procedure are presented.

In this paper, it is demonstrated on a simple example that both inter and intra-laminar damage models must be taken into account in the problem, meaning that playing with inter-laminar crack propagation only may provide inaccurate results.

The linear and non-linear material properties identified at the coupon level are then used at the upper stage of the pyramid, on an L-shaped beam. Comparison between tests and simulation demonstrate the efficiency of the modelling and analysis approaches implemented in SAMCEF. Results are provided for laminates made of UD plies.

2. Material models for inter and intra-laminar damage

The intra-laminar damage model for an unidirectional ply is described in [1,2]. The following potential with damage (here written in plane stress), named e_d, is used (1), where d_{11}, d_{22} and d_{12} are the damages related to the fibres, the transverse and the shear directions, respectively.

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

The thermodynamic forces are derived from this potential (as the derivatives of the potential with respect to the damage variables). They manage the evolution of the damages, via relations such as $d_{11} = g_{11}(Y_{11})$, $d_{22} = g_{22}(Y_{12},Y_{22})$ and $d_{12} = g_{12}(Y_{12},Y_{22})$. Non-linearities are introduced in the fiber direction, in tension and compression.

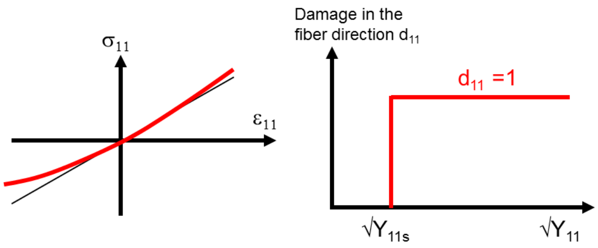


Figure 1: Material behaviour in the fibre direction, from testing.

A non-linear behavior is also considered in the matrix. Plasticity is taken into account, as permanent strains can't be ignored. All these ingredients are available in the model in order to represent the material behaviour observed during testing, as illustrated in Figures 1 and 2.

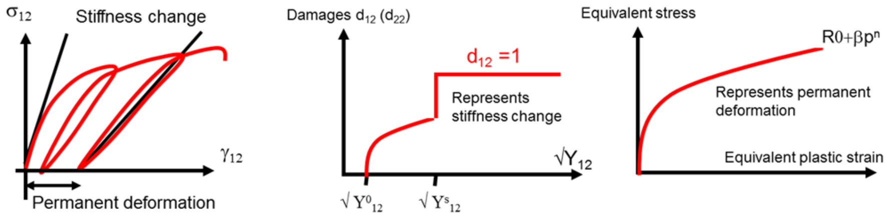


Figure 2: Material behaviour in the matrix, from testing

The intra-laminar damage model includes a total of 23 parameters, i.e. the 9 elastic properties in 3D (E^0_1, E^0_2, E^0_3, ν_{12}, ν_{23}, ν_{13}, G^0_{12}, G^0_{13}, G^0_{23}) and some parameters associated to the damage and plasticity (like Y^s_{11}, Y^0_{12}, Y^s_{12}, R_0, β and n in Figures 1 and 2).

The inter-laminar damage model, used to simulate delamination, is described in [3,4]. A potential including the relevant components of the strain tensor is assigned to the interface elements, leading to a cohesive elements approach. In (2), three damage variables d_I, d_{II} and d_{III}, related to modes I, II and III, are defined:

$$e_d = \frac{1}{2}\begin{bmatrix} k_I^0 \langle \varepsilon_{33} \rangle_-^2 + k_I^0 (1-d_I) \langle \varepsilon_{33} \rangle_+^2 \\ + k_{II}^0 (1-d_{II}) \gamma_{31}^2 + k_{III}^0 (1-d_{III}) \gamma_{32}^2 \end{bmatrix} \tag{2}$$

k_i^0 in (1) are the undamaged stiffness. The thermodynamic forces Y_i ($i=I,II,III$) are obtained by deriving (2) with respect to each d_i. For mixed mode loading, the damage evolution is related to the three inter-laminar fracture toughness G_{IC}, G_{IIC} and G_{IIIC} corresponding to opening (I), sliding (II) and tearing (III) modes. The equivalent thermodynamic force Y takes the following form:

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

In the model, the three damage variables have the same evolution over the loading, and a unique damage d is therefore managed for modelling delamination, that is $d=d_I=d_{II}=d_{III}$. The damage variable d, considering the failure state at the interface between plies, is related to the equivalent thermodynamic force *Y* with a function of the form *g(Y)*. In SAMCEF, three different functions *g(Y)* are available, leading to three possible cohesive laws, i.e. exponential, bi-triangular and polynomial.

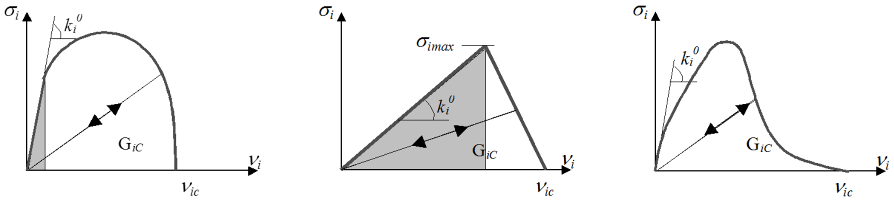


Figure 3: Cohesive laws available in SAMCEF.

3. Parameter identification procedure

Based on testing on a very limited number of coupons, it is possible to identify the 23 parameters involved in the intra-laminar damage model for unidirectional plies. Actually, 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 behaviour in each ply is determined. In practice, four series of tests are conducted, each series on a specific stacking sequence and/or loading scenario. As 5 successful tests are usually required, it means that 20 (=4x5) successful tests must be conducted to cover the 4 series. This is enough to identify all the 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 rather a procedure based on EXCEL sheets, which can be sped up by using some very simple FORTRAN programming. A comparison between tests and simulation is used to validate the identified values on a sequence not used for the identification.

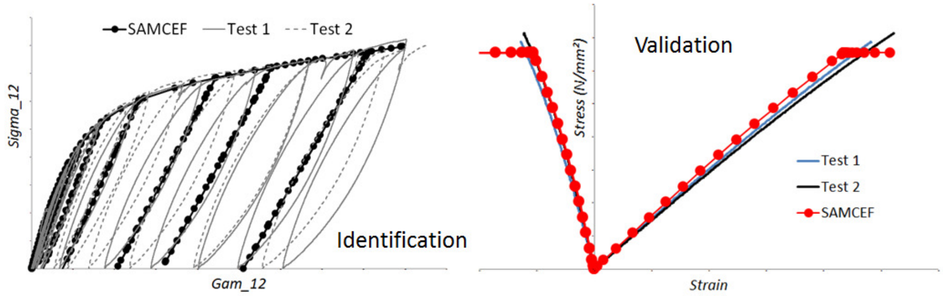


Figure 4: Comparison between test and simulation, for the identification and validation of the intra-laminar damage model parameters.

In order to identify the values of the parameters entering the cohesive models in the interface, specific tests like DCB and ENF are conducted. The corresponding finite element models are developed and a fitting between experimental tests and numerical results is conducted, as explained in Figure 5. The analytical solutions based on the beam theory are also used to tune the parameters of the material models assigned to the interface.

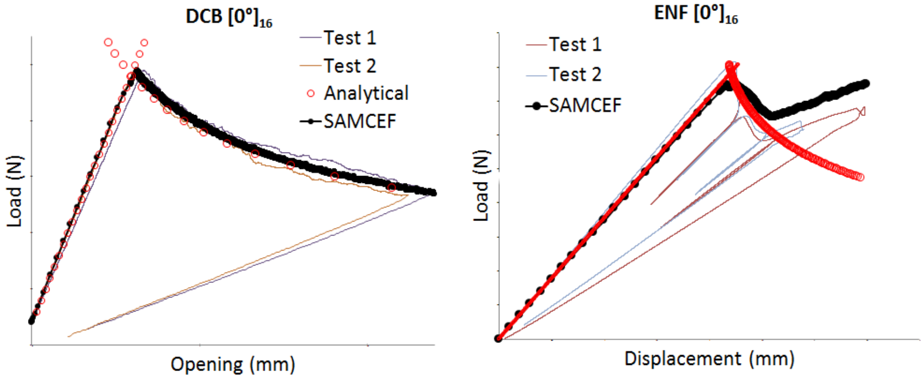


Figure 5: Comparison between test and simulation, for the identification of the inter-laminar damage model parameters

It is now demonstrated that, in a general case, it is essential to model the damage inside the plies besides delamination. This is illustrated for the ENF test case, as depicted in Figure 6, where simulation is compared to analytical solutions and to test results. It was observed in Figure 5 that for a $[0]_n$ laminate the behaviour 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 behaviour observed in the tests can only be reproduced when the damage inside the plies is modelled as well. It is seen actually that the analytical solution for delamination (red circles in Figure 6) is not able to reproduce the behaviour observed in the tests; including intra-laminar damage besides delamination in the simulation provides accurate results (black circles). Doing so, we note a very good agreement between tests (light lines) and simulation (dark circles).

4. Validation on elements and components with UD plies

Once the parameters are identified, the damage models are used at the upper stages of the pyramid of tests, and simulation, via virtual testing, becomes a companion of the physical testing. Please check the references [5,6] for the application of the current simulation strategy to a large hollow beam and to an impact case.

In this paper, an L-shaped beam submitted to two different load cases and boundary conditions is considered (Figure 7). The corresponding FEM models with some details are illustrated in Figure 8. The laminates are made up of 12 plies and the following stacking sequence is considered: $[60/-60/0/0/-60/60]_{s.}$ One element is used on each ply thickness, and interface elements are defined between each ply.

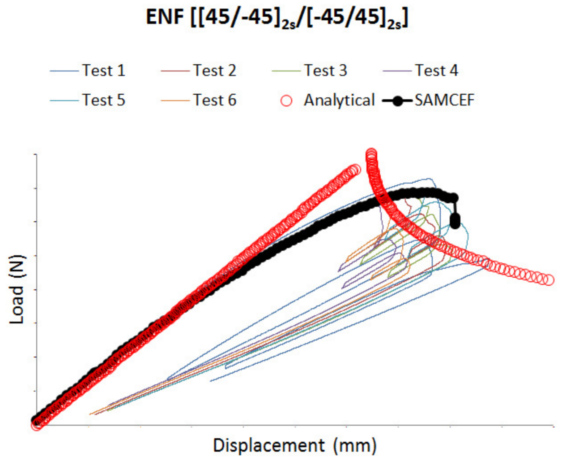


Figure 6: Inter and intra-laminar damages must be modelled: illustration on the ENF test case

The beam model is fully parameterized, and the user can modify the dimensions, the boundary conditions and the material (selection of the material properties in a data base defined as described in the previous sections) by assigning specific values to the parameters. For both configurations 1 and 2, specific rigid-flexible contacts and rigid body elements are defined in order to reproduce the loading and tests conditions. A sensitivity analysis with respect to the mesh refinement was conducted, and showed very little influence on the results. Elements of 5mm length are finally used, as they lead to a very low CPU time of 20 minutes on a personal computer with a single processor.

Results are provided in Figure 9 and 10. It is observed from simulation that damage mainly appears in the interfaces and leads to large sliding of the plies. Intra-laminar damage is also present, as observed in the tests. In Figure 8, the comparison between tests and simulations should be done carefully, as the times don’t correspond. Anyway, the global behavior is very similar.

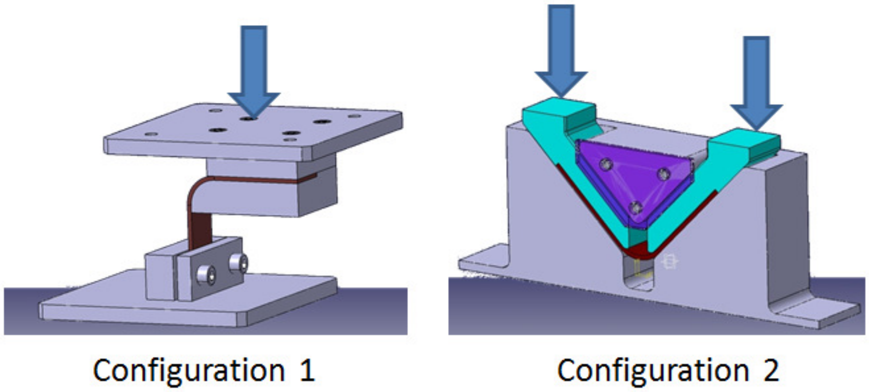


Figure 7: The two configurations of the L-shaped beam

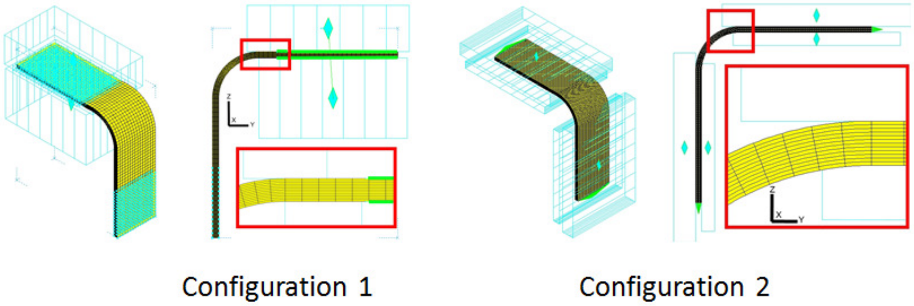
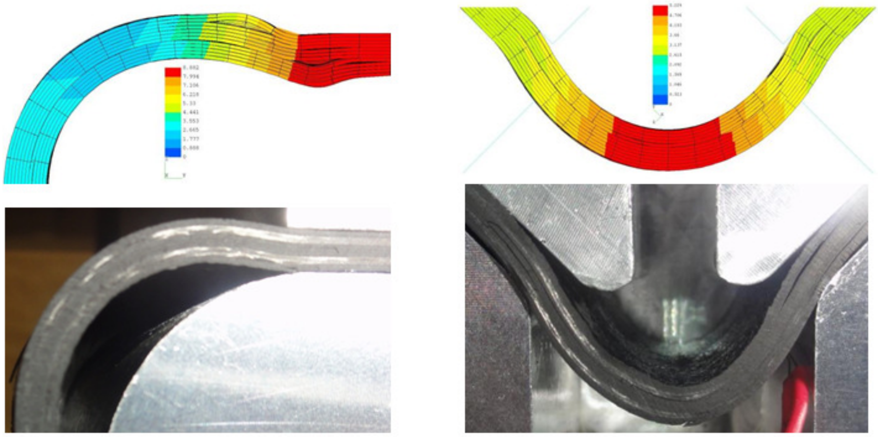


Figure 8: FEM models for both configurations

In Figure 10, the load-displacement curves are provided. It is seen that a very good agreement is obtained between test and simulation. For configuration 1, a slight variability is observed in the test results: it mainly impacts the post-critical part of the equilibrium curve and not the maximum load the structure can sustain. For configuration 2, the variability is a bit larger and influences the maximum load.

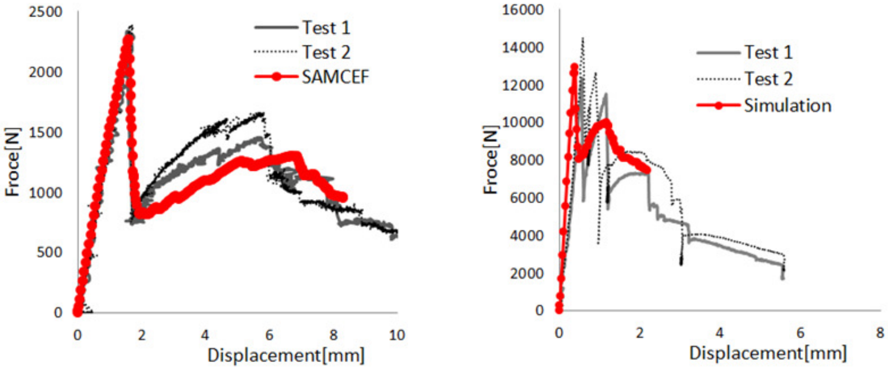
5. Conclusions

In this paper, the SAMCEF finite element code is used to assess the damage tolerance of laminated composite structures made of unidirectional plies. First, the inter- and intra-laminar damage models were presented. They can be used to model delamination on one hand, and damage inside the plies (that is fibre breaking, matrix cracking and de-cohesion between fibres and matrix) on the other hand. These models are able to reproduce the non-linear behaviour of laminated composites, including the permanent strains. The parameters used in the models are identified based on a small set of test results at the coupon level. These damage models are not only a nice set of equations, but can be used to solve practical applications. Once obtained at the coupon level, the values of those parameters are used to model and solve larger scale problems. Here, the case of an L-shaped beam submitted to two different loading and boundary conditions was considered. The very good agreement between tests and simulations demonstrate that this simulation strategy can be used as a companion to physical testing, and so reduce the number of tests needed to size the laminated composite structure.



Configuration 1 Configuration 2

Figure 9: Displacements and delaminations resulting from the loading (times don't correspond between tests and simulation)



Configuration 1 Configuration 2

Figure 10: Load-displacement curves: comparison between tests and simulation

6. References

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