Modeling and Simulating Progressive Failure in Composite Structures for Automotive Applications

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Abstract

In this paper, it is explained how composite structures, made of continuous fibers embedded in a polymer matrix, are designed and analyzed in the aerospace industry. The strategy is based on the building block approach, in which the knowledge on the composite material and structure is built step by step from the coupon level up to the final full scale structure. Damage is then discussed, as it can't be ignored when composites are concerned. The approach available in the SAMCEF finite element code is then described. It is based on the continuum mechanics approach, and allows studying the progressive failure of composites in the plies and at their interface (so considering delamination). The material models are described, and their use is illustrated at the coupon level. The identification procedure for this damage models is also discussed. It is therefore shown how this information of the material behavior can be used at the upper stages of the building block approach and so applied to larger scale structures. It is advocated here that this approach can be used for the automotive applications, leading to a transfer of technology from aerospace to automotive.

Introduction

Composite materials have been used successfully in the aerospace industry for many years due to their light weight and high mechanical performances. At the opposite, the amount of carbon fiber reinforced plastics (CFRP) used in the automotive industry is still limited to very specific applications and still not really appear as a reliable solution as far as structural components on the chassis are concerned. However, vehicle manufacturers and tier suppliers are facing the challenge of consistently maintaining high quality end-product with safety concerns while designing lightweight structures with fuel economy concerns. Carbon fiber-reinforced plastics, because of their high strength to density ratio, represent a serious alternative to classical metallic approach but generating the need to completely redefine the design methodology of the structural parts. Indeed, composite materials exhibit complex material behaviors, especially when the assumption of linearity cannot be done anymore. Thus the industry has developed very conservative design methods, negating many advantages that can be obtained from the use of composites materials.

Based on the experience from aerospace, this paper explains how to design high performance composite structures using advanced CAE tools, for the automotive applications. A complete approach for modeling and simulating highly nonlinear behavior, such as the damage propagation in composite materials, is then described. For those, new modeling approaches for delamination and in-ply damage using the Finite Element method will be described. The complete methodology for the non-linear material properties identification will be also discussed. This specific model can be used to study the progressive damage inside the ply, accounting for fibers breaking, matrix cracking and fiber/matrix de-cohesion. On the other hand, delamination can also be studied with the cohesive elements approach. These models are based on the continuum damage mechanics applied at the meso-level, and damage variables impacting the stiffness of the ply or of the interface are associated to the different failure modes. Specific applications, at the coupon or at the element/component level will illustrate this new capability, implemented (and native) in the SAMCEF finite element software.

The Design of Composite Structures

The structures and materials considered in this paper are thin-walled structures made of plies with continuous unidirectional fibers or woven fabrics, embedded in a polymer matrix. Such composite materials are extensively used in the primary structures of aircrafts. The design of structural composites for advanced applications is nowadays conducted with computers and numerical tools. It classically involves two disciplines. The first one, called Computer Aided Design

(CAD), aims at defining the overall geometry of the part, and the regions of laminates with their stacking sequence. It is linked to the Computer Aided Manufacturing (CAM) and provides specific capabilities for the manufacturing processes simulation. Such capabilities are used to determine the accurate fibers orientations and the deformation of the plies during the draping. The second discipline, called Computer Aided Engineering (CAE), is used to analyze the structural integrity of the composite structure when it is subjected to the expected loads [1,2]. In this paper, we only address CAE. It is well know from the aerospace industry that composite structures are designed with the building block approach [1]. This methodology is described in Figure 1, with the pyramid concept. The idea is to build the knowledge on the material and structural behaviors step by step, starting from the fundamental stage at the coupon level up to the full scale (i.e. the full wing or even the full aircraft). It has been observed over the years that simulation, and especially models based on the finite element method, are more and more used on the different stages of the pyramid, therefore becoming an important companion of the physical tests. It is indeed evident that tests can be expensive when repeated several times for different material configurations (e.g. different stacking sequences) or when small changes in the components geometry are studied. Finite element analysis must be predictive. When this condition is satisfied, simulation can replace some physical tests. Developing predictive simulation tools is clearly a challenge. The simulation tools should be able to address different attributes, covering static or quasi-static analyses, damage analyses, fatigue, dynamic response, crash, NVH, etc.

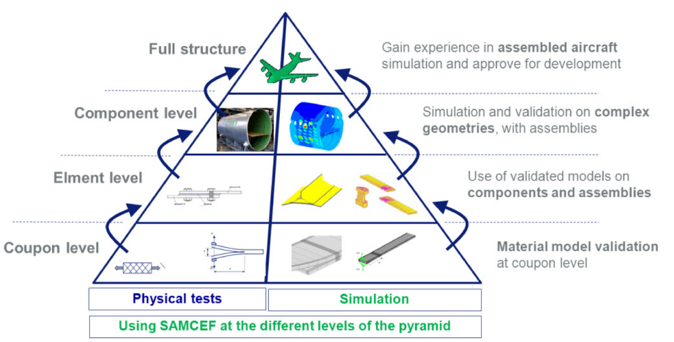

Figure 1. The building block approach applied to aerospace composite structures

In order to introduce effectively composite structures in primary parts of ground vehicles, the approach described in Figure 1 must be applied to automotive applications. As illustrated here, it appears that the first stages of the pyramids in Figures 1 and 2 are identical, and specific applications only appear at the next stages of the design process. The analyst of the automotive industry is therefore confronted to the same problems as the analyst in the aerospace sector: he also needs predictive simulation tools, for the attributes mentioned previously [3]. The aerospace approach can therefore be translated to the automotive sector. Understanding and being able to simulate the specific mechanical behaviors of composites is therefore important for the automotive industry.

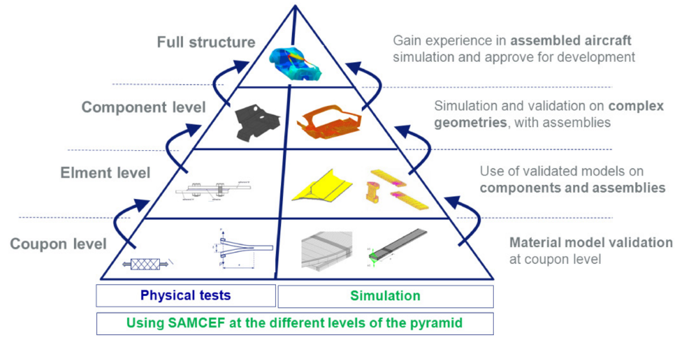

Figure 2. The building block approach applied to automotive composite structures

The Need for a Damage Tolerant Approach

When a laminated composite structure is submitted to a low energy impact, damage may appear inside the structure, especially between the plies. The main issue is that, depending on the energy of the impact, this damage is sometimes not visible (Figure 3). Such damage can appear during the manufacturing process or during the handling of the composite part. This implies that, in order to avoid overdesigns and not neglect the real behavior of composite materials, composite structures must be designed with a damage tolerant approach, allowing the presence of damage or assuming that damage may be present in the structure even when not visible, in order to determine safe material allowables for the next stages of the pyramid.

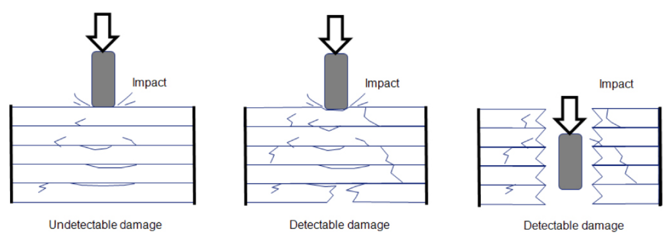

Figure 3. Illustration of the damage level depending on the energy impact

Several ways to include damage in the analysis are available. In this paper, the formulation is based on the continuum damage mechanics, and meso-models of the homogenized plies and of the interface are considered. These material models are determined based on the micro and meso-scopic behaviors of the composite material.

Modeling Inter-Laminar Damage

Delamination is one of the most critical causes of failure in a laminated composite structure. It results in the separation of two adjacent plies, leading to the propagation of an inter-laminar crack. In the finite element method, the cohesive elements approach is often used to model such cracks (Figure 4). Interface elements are then defined between the finite elements representing the plies. A specific material law with a softening behavior is then assigned to this interface. This allows the modeling of imperfect interfaces, which are interfaces where delamination can appear in case of excessive loading.

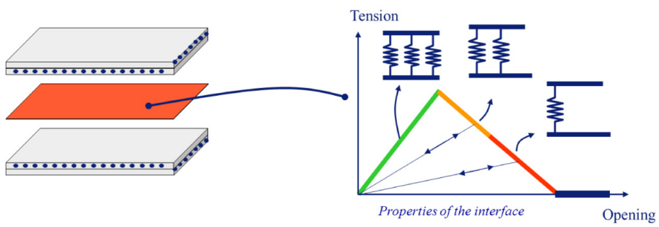

Figure 4. The cohesive elements approach

In SAMCEF, the Cachan model is used [4]. The potential (that is the energy) assigned to the interface elements is based on (1), where three damage variables d_I, d_{II} and d_{III}, related to modes I, II and III, are defined:

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

k_i^0 in (1) are undamaged stiffnesses. The thermodynamic forces Y_i ($i=I,II,III$) are obtained by deriving (1) with respect to d_i. For mixed 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:

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

The three damage variables have the same evolution over the loading, and a unique damage d is therefore managed for modeling 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 [5], leading to three cohesive laws, i.e. exponential, bi-triangular and polynomial. With this approach, it is possible to estimate the critical cracks, the propagation load, the maximum load the structure can sustain before a significant decrease of its strength and stiffness, and the residual stiffness during the inter-laminar cracks propagation.

In Figure 5, the Double Cantilever Beam (DCB) is studied. The simulation results are compared to the analytical solution based on the beam theory. In practice, the parameters of the cohesive law are determined considering that the numerical solution must fit the test and the analytical results.

Modeling Intra-Laminar Damage

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 degradation model is available in SAMCEF. This ply damage model relies on the development proposed in Ladeveze and LeDantec [6]. For intra-laminar damage, the following potential with damage, named e_d, is used (3), where d_{11}, d_{22} and d_{12} are the damages related to the fibers, the transverse and the shear directions, respectively. The thermodynamic forces are derived from this potential and 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 $d_{12} = g_{12}(Y_{12},Y_{22})$. A delay can also be defined in order to smooth the occurrence of the damages. Moreover, non linearities are introduced in the fiber direction, in traction and compression.

$$\begin{aligned}e_d&=\frac{\sigma_{11}^2}{2(1-d_{11})E_1^0}-\frac{\nu_{12}^0}{E_1^0}\sigma_{11}\sigma_{22}-\frac{\nu_{13}^0}{E_1^0}\sigma_{11}\sigma_{33}\\&+\frac{\langle\sigma_{22}\rangle_+^2}{2(1-d_{22})E_2^0}+\frac{\langle\sigma_{22}\rangle_-^2}{2E_2^0}+\frac{\langle\sigma_{33}\rangle_+^2}{2(1-d_{22})E_3^0}\\&+\frac{\langle\sigma_{33}\rangle_-^2}{2E_3^0}-\frac{\nu_{23}^0}{E_2^0}\sigma_{22}\sigma_{33}\\&+\frac{\sigma_{12}^2}{2(1-d_{12})G_{12}^0}+\frac{\sigma_{13}^2}{2(1-d_{12})G_{13}^0}+\frac{\sigma_{23}^2}{2(1-d_{22})G_{23}^0}\end{aligned} \quad (3)$$

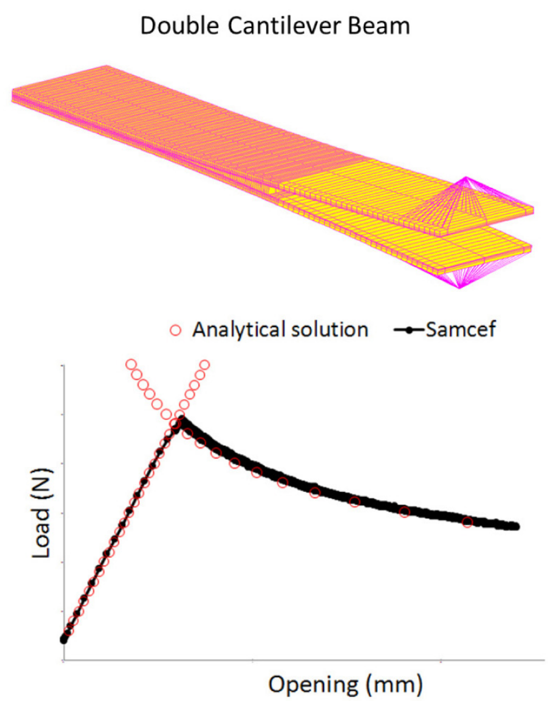

Figure 5. The Double Cantilever Beam test case

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 6: non linearity in the fiber direction, non linearity including plasticity in the matrix.

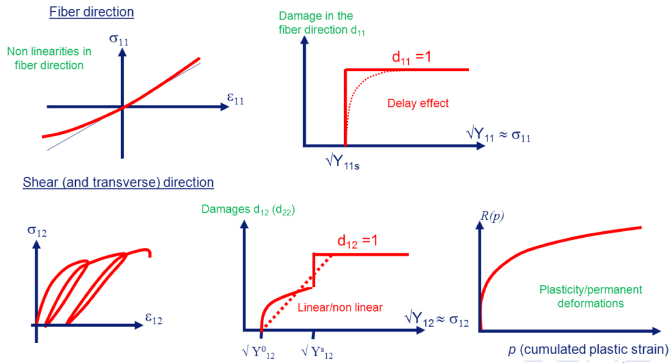

Figure 6. Non-linearities in the damage model for the UD ply

It is clear from Figure 6 that the damage law includes several parameters necessary to define the material behavior, such as Y^0_{12}, Y_{11s}, R(p), etc. The value of these parameters must be identified in order to be able to use in a correct way the damage model. This identification procedure is based on tests at the coupon level, which is the first stage of the pyramid of Figures 1 and 2. As explained in [6], standard coupons with specific stacking sequences like 0/90 and 45/−45 sequences are used in a loading/unloading scenario in order to identify the value of the damage parameters (Figure 7). For laminates made up of unidirectional plies, physical tests on 3 different stacking sequences must be conducted. The 0/90 laminates are tested in traction and compression. The 2 other sequences are tested in traction in a loading/unloading scenario, up to the final failure. The test machines are standard; the only specificity is to be able to define loading/unloading sequences, as depicted in Figure 7.

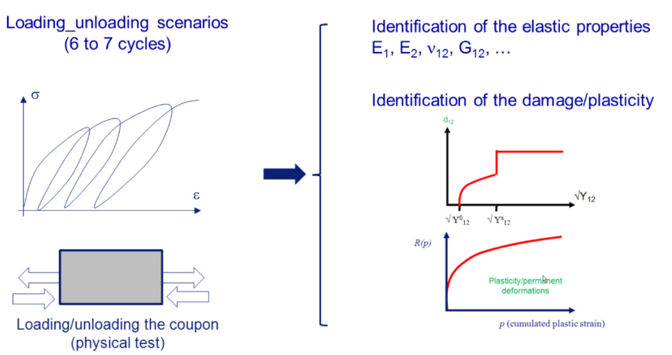

Figure 7. Identification of the parameters values on coupons

In Figure 8, the case of a laminate with a stacking sequence made of 45°/−45°plies is presented. The simulation results with the identified parameters are compared to a reference result. It is clear that the non-linear behavior of the composite material is well identified, together with the permanent deformations (plasticity). In Figure 9, it is shown that when non-identified (or badly-identified) parameters are used, the simulation results are not in good agreement with the reference results. It is therefore of paramount important to identify in a correct way the value of the parameters for the composite damage models.

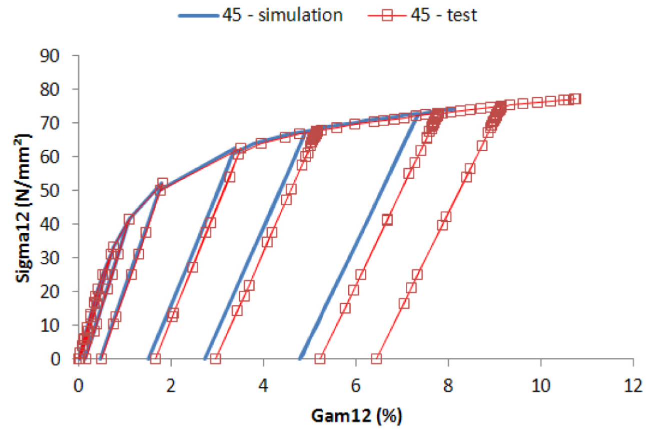

Figure 8. Material response and comparison with a simulation when the identified parameters are used

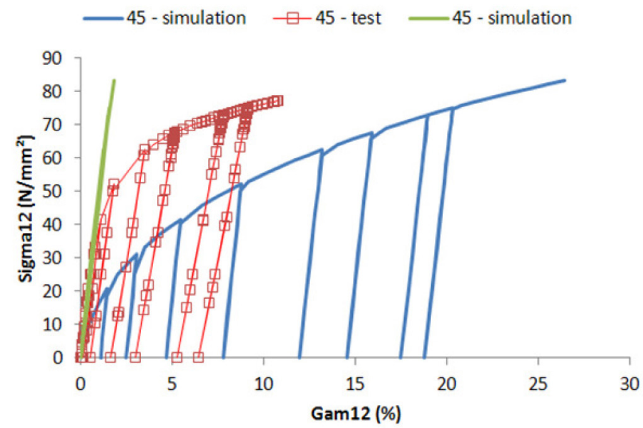

Figure 9. Same problem as in Figure 8, but with non-identified values of the parameters

In practice, this 45/−45 laminate is used to identify the parameters, so it is normal that simulation fits the experimental results. When these parameters are identified, simulation can be used for validation on coupons with stacking sequences not used for the parameter identification. Here, we consider a [67.5/22.5]2s laminate. This stacking sequence was not used for the identification. The prediction of the mechanical behavior obtained from simulation is compared to the test results in Figure 10. The agreement is very good, meaning that simulation can now replace physical tests at the coupon level, for any stacking sequence and ply number. The identified parameters can now be used at the upper stages of the pyramid, and problems of more complex geometries can now be addressed, as illustrate in the following section.

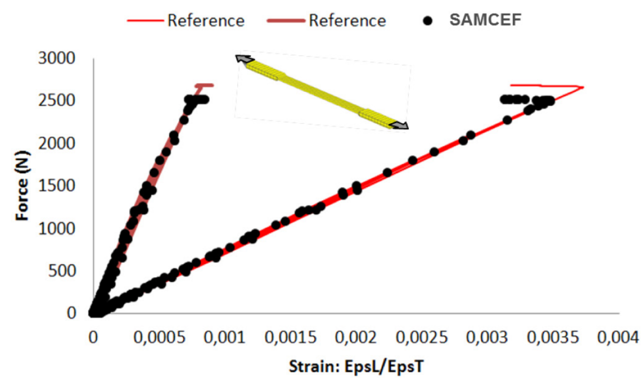

Figure 10. Validation of the parameter identification on another stacking sequence at the coupon level

Illustrations

When the parameters of the damage laws, for inter and intra-laminar damage, have been determined at the coupon level as described in the two previous sections, they can be used at the upper stages of the pyramid of Figures 1 and 2.

Impacted Plate

As depicted in Figure 3, when a plate is submitted to a low energy impact, damage may appear, even if it is not visible from the outside. We consider here the problem of a plate made of 7 plies submitted to such a low velocity impact (Figure 11). As illustrated in Figure 12, delamination will appear between the plies (red means locally completely delaminated). A typical subsequent analysis (not reported here) consists in submitting the impacted plate to compression. The resulting ultimate strength is then compared to the value obtained after a compression without impact.

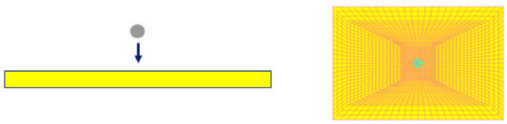

Figure 11. Impacted composite plate

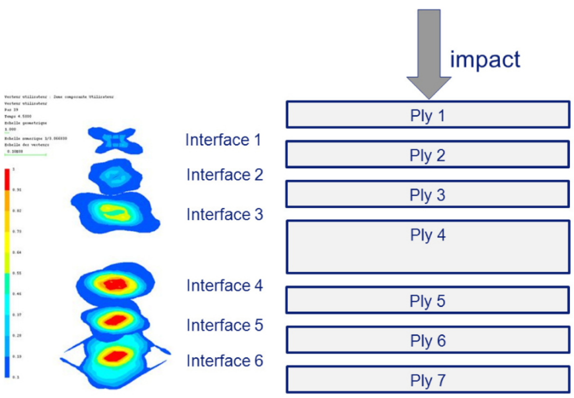

Figure 12. Impacted composite plate; resulting delamination

Large Scale Stiffened Panel

An aero-structure illustrated in Figure 13 is considered, but the methodology can be applied to any composite structure, for instance in an automotive application. As illustrated in Figure 12, a stiffened composite panel is submitted to compression. Some imperfections are taken into account, such as initial separation of the skin and the stiffeners on some locations. It is shown that there is a good agreement between test and simulation results, not only for the deformed shapes and damages, but also for the load/displacement curve. The SAMCEF 1 result of Figure 13 only considers geometric non linearities, while the SAMCEF 2 curve includes also the material damage and the de-cohesion between the stiffeners and the skin. It is clear that only considering the kinematic of the buckling and post-buckling behaviors is not sufficient to determine the whole non-linear behavior of the panel, including maximum load and final failure.

Summary/Conclusions

In this paper, it was explained how the building block approach is used for the design and analysis of composite structures in the aerospace industry. This approach should be used also for automotive applications. Doing so, the knowledge of the composite is built up from the coupon level (material level) up to the full scale level (structural level). It was also demonstrated that damage must be considered in the design of composites and that a damage tolerant approach should be considered. The damage models available in the SAMCEF finite element software were described, as well as the identification procedure of their parameters at the coupon level. It was then shown how larger scale composites can be analyzed. This demonstrated the maturity of the damage modeling methods available for aerospace composites applications. Such an expertise should clearly be transferred to the automotive sector, as far as the design of primary structures made of continuous fibers is concerned.

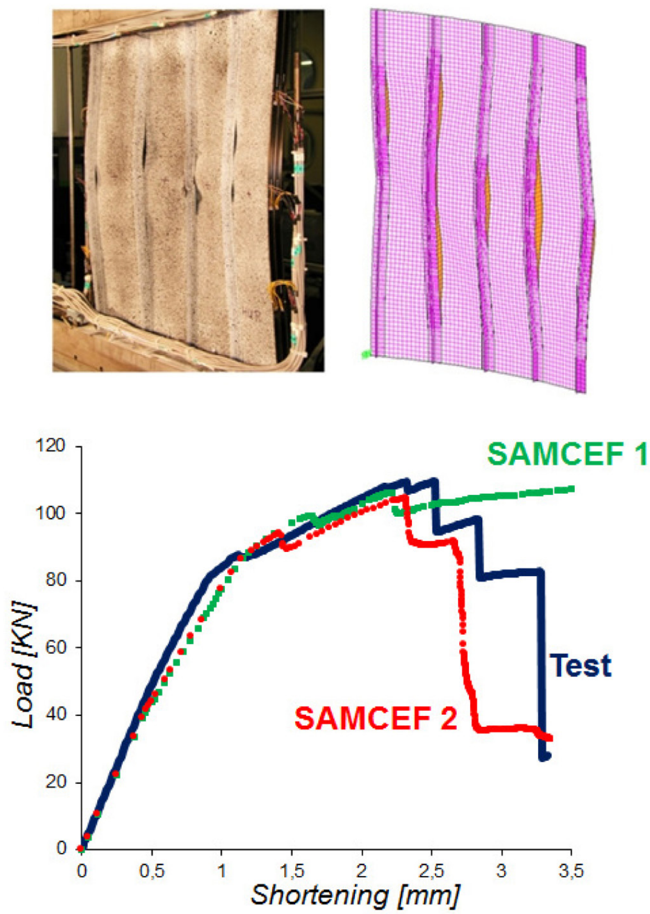

Figure 13. Stiffened composite panel submitted to a compression: comparison test/simulation

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Contact Information

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