ADVANCED MECHANICAL JUSTIFICATION FOR LAUNCHER COMPOSITE STRUCTURES

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Abstract

To prepare the future launcher development programs, Astrium Space Transportation (AST) is working on the progressive implementation of new advanced mechanical justification approaches for composite structures, in the frame of a dedicated Roadmap. An important working axis of this Roadmap is related to composite damage modelling: an evaluation of damage models recently implemented in the Finite Element Software SAMCEF© is currently being performed. The presentation will show, through some examples, first results from this evaluation, highlighting the benefits that can be expected from these advanced methods.

1. Introduction

Current mechanical justification approaches for launcher composite structures require significant experimental validation, at the various level of the Test Pyramid. To improve their efficiency for the development of future launcher composite structures, it is important to work on the implementation of new advanced methodologies. As illustrated hereunder in Figure 1, various composite structures can be found in a launcher, mainly based on carbon fibre / epoxy resin:

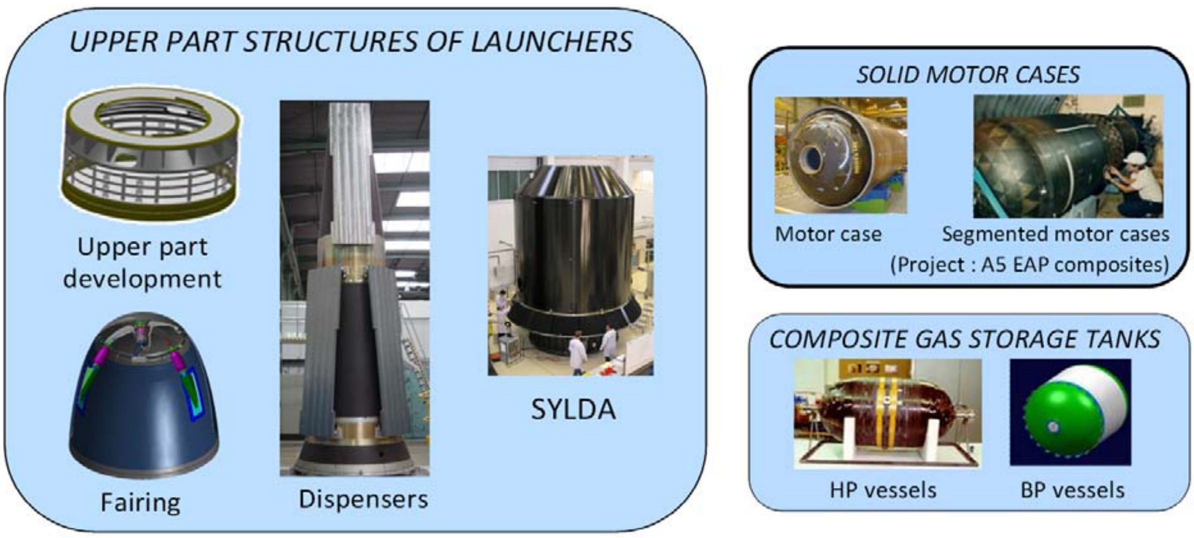


Figure 1. Examples of launcher composite structures

On Ariane 5, the most important proportion of composite can be found in the launcher's upper part, because the impact on performance is the most significant in this area. Moreover, because of the continuous need of increasing the payload mass versus the launcher global weight, the global percentage of composite will continue to increase for the next generation launchers. For this reason, it is particularly important to improve the robustness and the efficiency of our mechanical sizing and justification approaches for composite structures. This will allow reducing our life-cycle costs, as well as the structure development duration, what is an essential challenge for the next generation launchers.

2. Astrium-ST Roadmap related to Advanced Justification Methods

As illustrated in the macro-logic presented in Figure 2, for future launcher development programs, it is important to increase progressively the use of theoretical approaches, introducing new Advanced Methods:

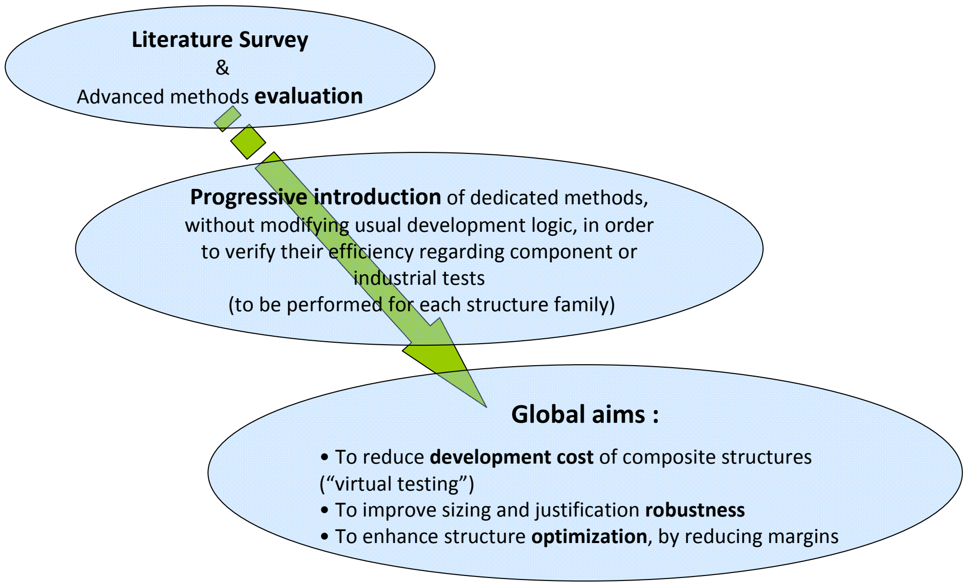


Figure 2. Macro-logic of advanced methods implementation

The research and development activities necessary to improve composite structure justifications have been identified in a Roadmap, defining different topics to be developed and how to increase their readiness levels in order to apply these new approaches for future launcher structures.

An important working axis of this Roadmap is related to composite damage modeling. Indeed, on the basis of extensive academic works on this topic for a long period, numerous improvements have been implemented these last years in industrial software items. For this reason, we are currently performing an evaluation of the damage models recently implemented in the Finite Element Software *SAMCEF©*. Three main composite damage models are available in the last version of this Software, implemented on the basis of LMT Cachan advanced works in this field:

- Intralaminar damage models: 2 versions exist, the first one dedicated to Unidirectionnal composites (cf. [1]), and the second to 2D Woven Fabric composites (with only in-plane fibre directions, cf. [2]). These models allow representing the impact of matrix cracking on the composite behavior, as well as the brittle fibre failure, but without accounting for delamination.

- Interlaminar damage models: delamination initiation and propagation phenomena are represented through the use of cohesive interface elements, which are integrated between two consecutive layers with different orientations (cf. [3]). In the first version of these models, no coupling with intralaminar damage is taken into account, what can be accurate enough when this damage mechanism is not predominant.
- Enhanced LMT damage model: the last version of LMT damage model implemented in Samcef (cf. [4]) has been developed to take into account the interaction between intralaminar and interlaminar damage. Such coupling phenomenon is particularly important in singular areas (e.g. holes, local load introduction, discontinuities …).

An essential point for the use of these new approaches is the identification of the material damage properties: it is not sufficient to learn how to use these advanced models, it is also mandatory to learn how to characterize efficiently the corresponding damage parameters, in an industrial context.

In the next part of the presentation, we will show, through examples, some results of the evaluation of those new advanced justification approaches, highlighting the benefits that can be expected from them.

3 Illustration examples about methodological climb in maturity

3.1 Identification methodology of ply damage model

This example illustrates the identification of the material parameters needed for the 2D intralaminar Woven Fabric damage model (cf [2]: model developed by LMA, on the basis of LMT UD model). This model is based on a thermodynamic formalism, and defining the strain energy density such as:

$$\mathrm{E}_{\mathrm{D}}^{\mathrm{cp}} \equiv \frac{1}{2}\left[\frac{\langle\sigma_1\rangle_+^2}{E_1^0(1-d_1)}+\frac{\langle\sigma_1\rangle_-^2}{E_1^0}-2\frac{\upsilon_{12}^0}{E_1^0}\sigma_1\sigma_2+\frac{\langle\sigma_2\rangle_+^2}{E_2^0(1-d_2)}+\frac{\langle\sigma_2\rangle_-^2}{E_2^0}+\frac{\sigma_{12}^2}{G_{12}^0(1-d_{12})}\right] \tag{1}$$

This expression introduces the damage variables (d_1, d_2 and d_{12}), representing the different damage mechanisms of the ply. The objective of the identification presented here is to characterize the damage kinetic related to d_{12} variable, i.e. linked to the micro-cracking inside the matrix and at the fiber/resin interface, and formulated by the following equation (2):

$$d_{12}=\left\langle\frac{\sqrt{\underline{Y}}-\sqrt{Y_0}}{\sqrt{Y_c}-\sqrt{Y_0}}\right\rangle_+ \tag{2}$$

where Y is the maximum equivalent thermodynamic force corresponding to this damage and its coupling with fibre stress, and Y_o and Y_c are respectively the initiation threshold and the critical value of damage evolution. The approach used consists in performing loading/unloading cycles of increasing level on ((±45°)n)s lay-up samples, introducing plane shear stress in the fabric, as illustrated on figure 3.:

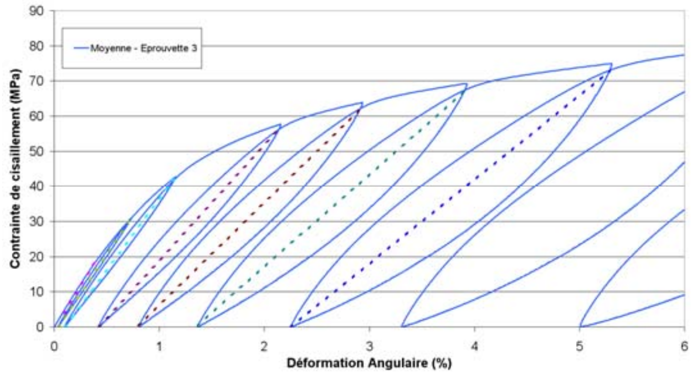


Figure 3. Loading / Unloading cycles inducing in plane shear

Each cycle is then exploited, in order to compute the corresponding secant modulus, residual strain and damage equivalent thermodynamic force. The different points are then plotted on a curve, what allows identifying the damage parameters by linear interpolation:

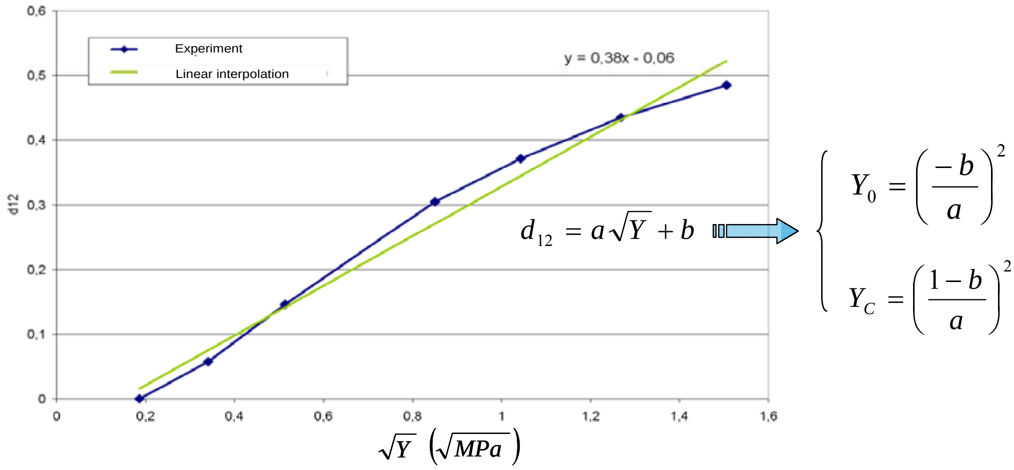


Figure 4. Identification of in plane shear damage parameters

Other parameters of this damage model, such as damage coupling and anelastic strain law properties, are also identified in a similar way. At the end, the relevancy of the identification is verified by simulation / experiments comparison, what shows a very good correlation on the following graph:

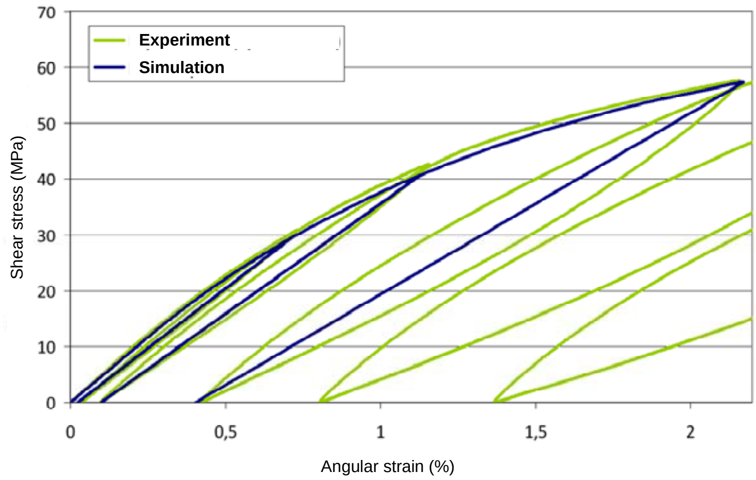


Figure 5. Validation of the identification performed

3.2 Simulation of delamination initiation and propagation

This second example shows an evaluation of the LMT interlaminar damage model, without coupling with intralaminar damage. In this approach, delamination initiation and propagation is represented by the use of cohesive interface elements, introduced in the mesh between composite plies, and representing the matrix link between them. These interface elements follow a behavior law defined from the strain energy density W:

$$W\left[N.mm^{-1} = mJ.mm^{-2}\right] = \frac{1}{2}\left[\frac{\langle\sigma_{33}\rangle_-^2}{K_3^0} + \frac{\langle\sigma_{33}\rangle_+^2}{K_3^0(1-d_3)} + \frac{\sigma_{32}^2}{K_2^0(1-d_2)} + \frac{\sigma_{31}^2}{K_1^0(1-d_1)}\right] \tag{3}$$

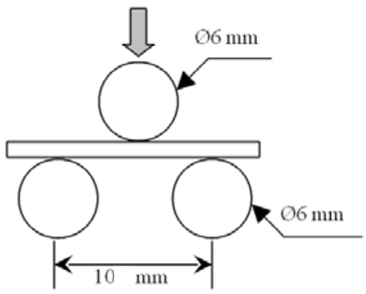
No damage in compression

Possible damage in tension

Possible damage in shear

The d_3 variable represents the damage in mode I (delamination opening), and d_1 & d_2 account for mode II and III (delamination shearing and tearing). The evolution of these variables is driven by an adapted kinetic, described in detail in ref. [3], in link with the critical energy release rates of the material (G_I^c & G_{II}^c) and the interface strengths in tension σ_3 and shear τ_{13}.

This approach using cohesive elements was applied to simulate a Short Beam Shear test, often used to evaluate material interface performance in shear. The principle of this test, sketched in figure 6., consists in a 3 points bending loading with a small distance between the supports, what allows introducing dominant interlaminar shear in the sample:



$$\tau_{rupt} = \frac{3}{4}\frac{F_r}{Bh} \tag{4}$$

Figure 6. Validation of the identification performed

According to the corresponding standard [5], the interlaminar shear stress level reached at failure can be computed with equation (4), where F_r is the failure load level, B the sample width, and h its thickness. This expression is derived from analytical computation of short beams, taking into account transverse loading. According to this standard, it must also be verified, prior to the exploitation, that the failure mode is valid, with a dominant interlaminar shear fractography.

A finite element model of the sample with the test conditions has been generated, as shown in figure 7.. Considering the symmetry of the system, only the half of the sample has been modeled. The steel rollers (used for support and loading introduction) are also included in the simulation, with contact conditions between them and the composite sample. Moreover, cohesive interface elements have been introduced between each composite layer, with the objective of representing initiation and propagation of delamination inside the sample. On the following figure, the deformed shape of the computed sample is represented at different loading level, showing the delamination propagation in link with the corresponding points of the Force(displacement) curve. Delamination can be visualized through the corresponding damage variable, varying between 0 (blue ➔ no damage) and 1 (red ➔ complete delamination):

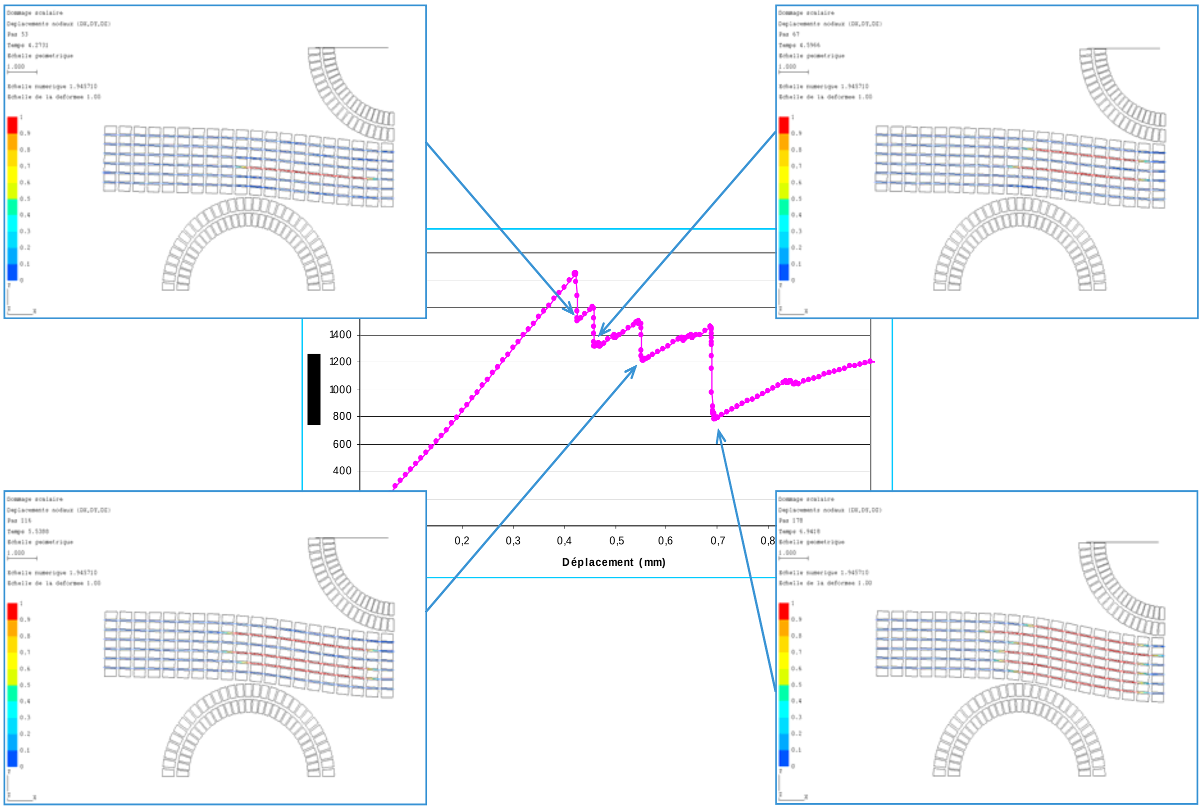


Figure 7. Delamination progression inside the sample

This analysis shows that the first discontinuity on this curve is induced by the delamination initiation and propagation at mid-thickness of the sample. This location is coherent with the observed and theoretical behavior of the specimen, because the maximum interlaminar shear stress appears in this area. The following discontinuities are associated with the same delamination phenomena, which appears at the other interfaces, and progressively concerns the whole thickness of the lay-up, between the lower and the upper rollers.

The comparison with experimental measures shows qualitatively a good coherency: the Force(displacement) curve presents similar discontinuities generated by delamination, with a predominance of decohesion at mid-thickness. However, some differences can be observed:

- The first delamination is over-estimated by simulation, what can be probably explained by more complex damage phenomena, like coupling between intralaminar and interlaminar damage, and indentation of the rollers in the sample, which are not represented by the cohesive model used;
- Experimentally, delamination propagates until the end of the sample, whereas in the simulation it stops in the lower roller area. This is probably linked with dynamic propagation during the failure.

4 Conclusion and prospects

The evaluations of composite damage models running at Astrium Space Transportation, illustrated in this paper by examples, show numerous benefits brought by such advanced modeling: they can account for material non linearity, and allow continuing computation after local failure, like interlaminar delamination or first ply failure. As a consequence, critical loads to failure are better estimated. In synthesis, we can say that the mechanical degradation phenomena of composite structures are better represented by those approaches, inducing an improved understanding and mastering of their mechanical behavior. The resulting improvement of the theoretical prediction will allow reducing the experimental part of the Justification Pyramid, by reinforcing simulation part.

However, some improvements still need to be performed for an industrial use. For example, convergence and artificial localization of damage often appear with these models, which require the use of regularization techniques to avoid these problems. Moreover, specific numerical & modeling strategies must be developed to reduce computation time, like parallelization & multi-scale approaches. There is still a lot of work to perform for the climb in maturity at Astrium-ST, particularly concerning the “enhanced damage model” recently implemented in SAMCEF©, taking into account coupling between intralaminar and interlaminar damage.

Finally, a strong support of agencies is needed for the progressive implementation of advanced justification methods, in order to be ready for future launcher developments, in a few years. In parallel, it is important to introduce dedicated instrumentation set-up during next experiments (field measurements, damage inspection…), as it is an essential step for a robust validation of damage models.

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