ROSPA: Robustness in Safety Performances Analysis

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Abstract

Fuel consumption issues are currently forcing car manufacturers to increase the use of lightweight materials in the development of new vehicles. Among those materials, composites are the most interesting solution. Unfortunately, they show a spread in performance characteristics due both to the manufacturing process and to the material providers, thus limiting the use of this material to niche productions. This issue could be solved once a more robust design is in place, taking into account the scattering of material characteristics when evaluating global performances. This document describes the work done in the framework of the PRACE SHAPE pilot experiments, aiming to develop with the help of a HPC approach a new robust methodology (where a robust approach means a statistical one, compared to the old deterministic approach) to assess the behavior of composite materials with respect to their resistance to impact load cases, which usually drive vehicle design.

Introduction

AMET [1] is a high-tech engineering company, active in the design and development of mechanic and mechatronic products and processes, based on numerical simulation. AMET, the acronym of Applied Mechatronic Engineering & Technologies, has been established in 1999, as a spin-off of the Mechatronics Laboratory of the Politecnico di Torino.

AMET is certified by TÜV NORD [2] according to quality standard ISO 9001:2008. The company's mission is to provide its customers with best-in-class solutions - i.e. methodologies, technologies and engineering services - for the design and development of industrial products, exploiting an integrated multi-domain model-based approach, to assure optimum system performance.

The company's customers are mainly the R&D departments and in the testing departments of large companies. AMET continuously collaborates with Universities and Research Institutes and promotes research and innovation activities.

The company's main market is the transportation industry and in particular automotive; furthermore railways and aerospace, apart from general industry, mechatronic and energy industry.

Due both to its dimensions and expertise, AMET main focus is to provide engineering services for the development of projects with high complexity; for this reason targeting niche projects with high added value is perfectly coherent with the company strategy. In the automotive industry, niche projects usually recur to the use of exotic materials, such as composites; while this approach grants some clear benefits, as in terms of weight and stiffness, it has even some weak points, mainly for what concerns the behaviour of this kind of materials for what concerns the prediction of their behaviour in terms of impact resistance. A more reliable knowledge of how these materials react under impact translates immediately in a better estimation of the safety offered by the vehicles made with these materials.

For the above reason, usually a costly and time consuming experimental campaign is planned to ensure the robustness of the design with respect to the scattering in terms of materials characteristics that is inherent in the recourse to those materials.

In this framework, AMET and Cineca have partnered in the PRACE SHAPE (SME HPC Adoption Programme in Europe) pilot [7] project to investigate the direct and mutual influence of the characteristic parameters that constitute the material card of a composite material, as used in commercial Finite Elements (FE) codes, in order to have a better understanding of these phenomena with the final aim to be able to deal with development projects with a higher confidence in the numerical results, thus reducing the costs of the experimental tests.

Project description

A large part of this project has been focused on the development of a methodology capable of replicating by means of numerical simulation the experimental tests used for the characterisation of the composites materials both for what concerns mechanical characteristics and impact resistance. The study can be summarised in the following main phases:

- theoretical study of phenomena involved in impacts. In this case, impact load and specimen motion and deformation and the related mechanisms of damage;
- choice of a commercial FE code capable of representing, with a reasonable degree of approximation, the above mentioned phenomena;
- choice of proper approximate functions suitable for representing the mechanical behaviour of materials, in this particular case to model composite materials;
- choice of the proper damage model capable of simulating intra-laminar breakage mechanism (delamination), fibre breakage and matrix rupture, in order to properly evaluate energy absorption and damage resistance;
- evaluation of the contact algorithms in order to correctly simulate the interactions between impact load and specimen;
- choice of the continuum element able to represent large structures with many layers each with different orientations and, potentially, with different materials;
- use of Design-Of-Experiments (DOE) [3] techniques to identify of the most effective parameters of chosen material behaviour functions;
- system identification based optimization to fit numerical with experimental results coming from standard tests;
- FE prototype model building.

Project work

As a first step, a comprehensive specimen model has been built to be able to perform all the required analysis together, in order to condense the number of runs; in the Figure 1 below a sketch of the model is shown:

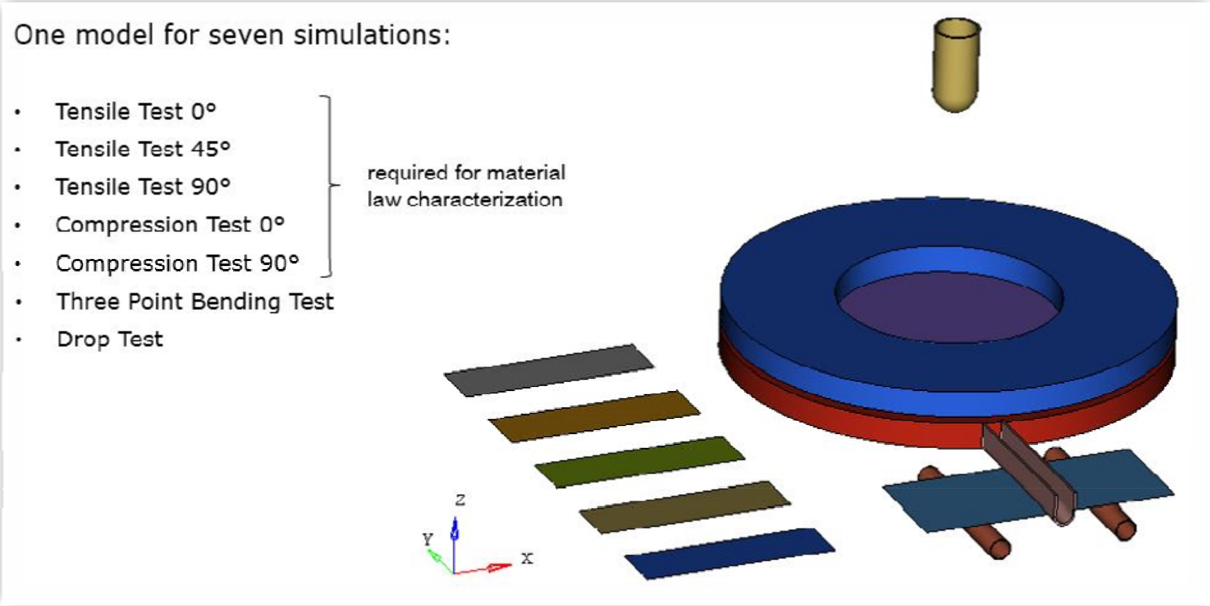

Fig. 1: specimen model sketch.

Specimens where modelled taking into account manufactured layers orientation and true global and per-ply thickness. Even dealing with small models, samples are few cm of characteristic length with an average element size of 3 to 5 mm, the computational effort is quite huge.

An in-house developed tool, based on an external optimisation engine has been used to fit the material variables with experimental specimen data coming from standard tests performed on from 4 to 6.5 mm thick samples, 20 to 80 layers each (15 specimens for each test/material):

- tension test: lamination 0°, 45°, 90°
- compression test: lamination 0°, 90°.
- three point bending test: lamination 0°, 45°, 90°

Constitutive approximate functions relating mechanical properties parameters for each specific composite material have been then defined.

The material fitting flow-chart is depicted below in Figure 2.

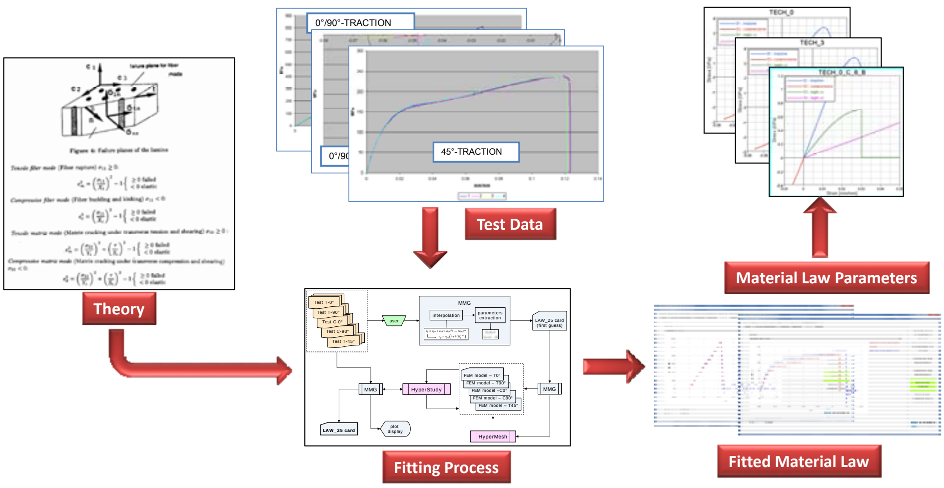

Fig. 2: material fitting flow-chart.

Dealing with large models and many runs, a macro-scale approach has been preferred, as shown below in Figure 3:

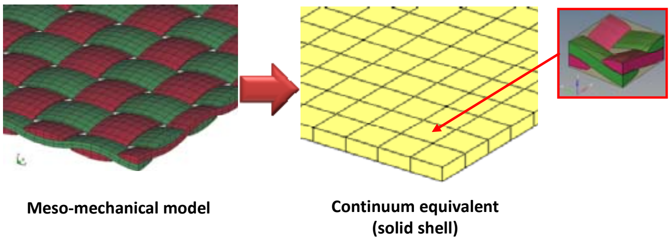

Fig. 3: visual description of the adopted macro-scale approximation.

The numerical representation of composite laminates generally follows two main directions:

- two dimensional models (shell approach);
- three dimensional models (solid approach);

each one characterized by its own merits and limits. A common point of these two methodologies is the “smearing” operation of mechanical properties of the constituent fractions, fibre and matrix, in order to represent each ply as a homogenized equivalent continuum. In both cases the properties along each of the two (or three) coordinate directions can be assigned through dedicated material models in order to describe the anisotropic nature of the real material.

In this project the relatively new thick shell (TSHELL) element was chosen. The great advantage with respect to the shell element, which likewise allows for user-defined integration and material angle definition, is the possibility to define the real geometric thickness of the ply and then of the related contacts; this is particularly important when modelling delamination (tiebreak).

Each single layer has been modelled and given the proper through-thickness material distribution and orientation as shown in Figure 4:

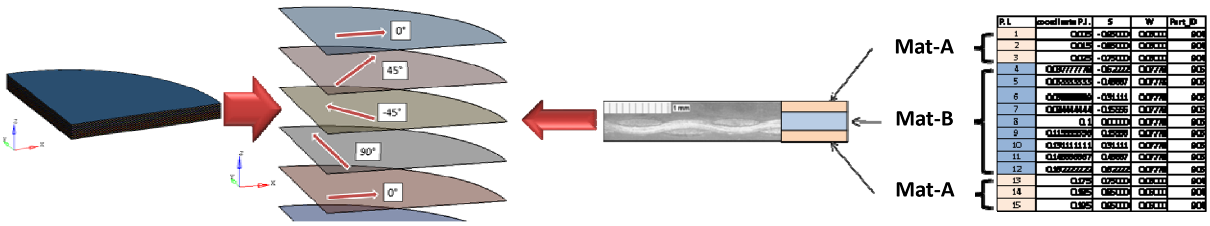

Fig. 4: visual description of the layer properties modelling.

Delamination damage was implemented in the simulation through the usage of a surface-to-surface tiebreak contact algorithm based on the bonding properties of interlaminar interface, as decribed in Figure 5:

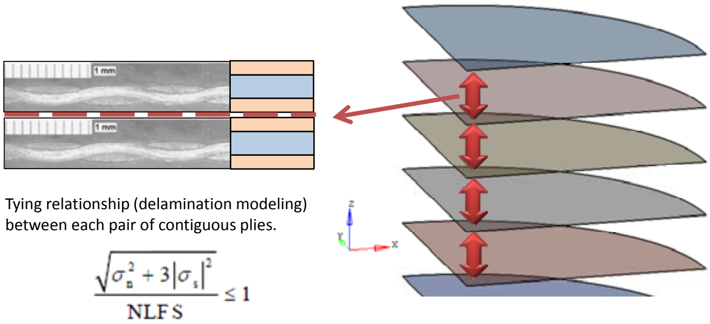

Fig. 5: visual description of delamination damage modelling.

Only opening Mode-I has been considered as failure trigger, even if this interlaminar failure model takes into account of shear effects that are smeared into a global equivalent stress, as shown in Figure 6:

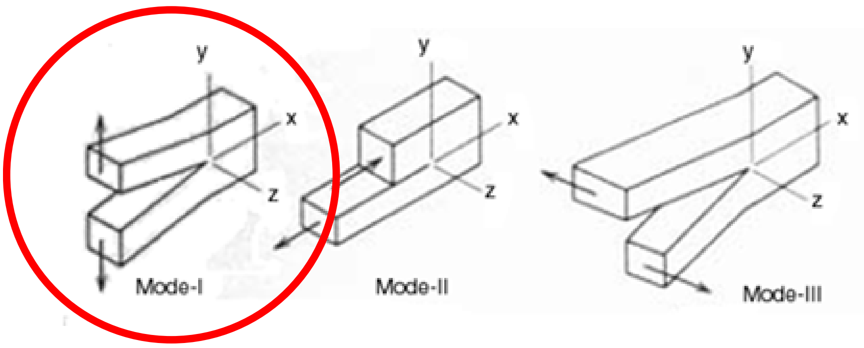

Fig. 6: interlaminar failure modes of composite materials.

The chosen anisotropic material constitutive law [4,5] comprehensive of the damage model is fully characterized by 30 parameters; with admissible assumptions they can be reduced to 23 for an Uni-directional fabric material (UD) and to 15 for a Bi-axial fabric material (BIAX). A comprehensive tool was built by CINECA to handle parameter definitions, FE solver run management, data collection and analysis. Figure 7 and 8 present screenshots of the pre-processing and post-processing phases.

A complete study to identify all the effects and interactions has lead, even considering the smallest hypothesis case, to the necessity of handling a large number of FE runs (2^{15} = 32768). The numerical campaign was performed on a Tier-1 HPC infrastructure provided by CINECA, an x86_64 machine named PLX, is fully described within CINECA web site [6]. Each run, at 4 parallel threads, needed from 1 to 48 cpu_hours, for a total of about 300.000 cpu_hours. The number of parallel threads used was limited by the available license of the commercial solvers. For confidentiality issues, we prefer not to mention which commercial solver was used.

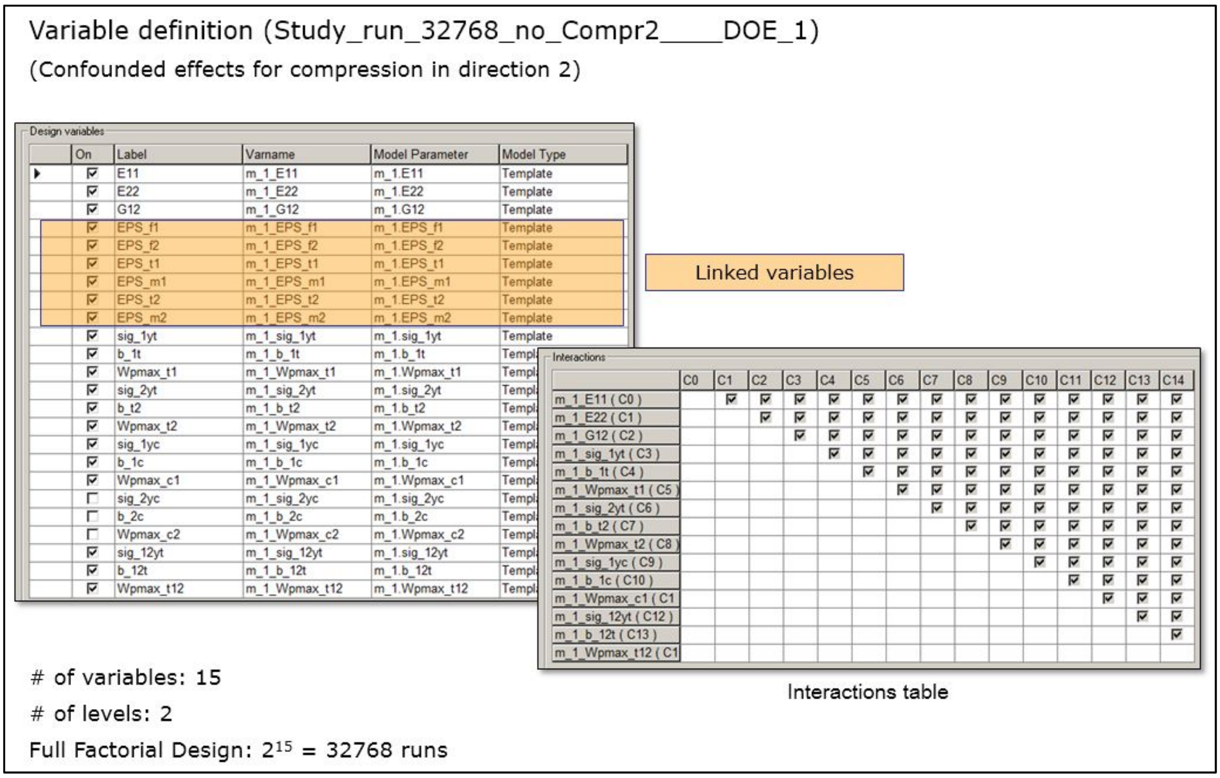

Fig. 7: preprocessing phase, parameter choice.

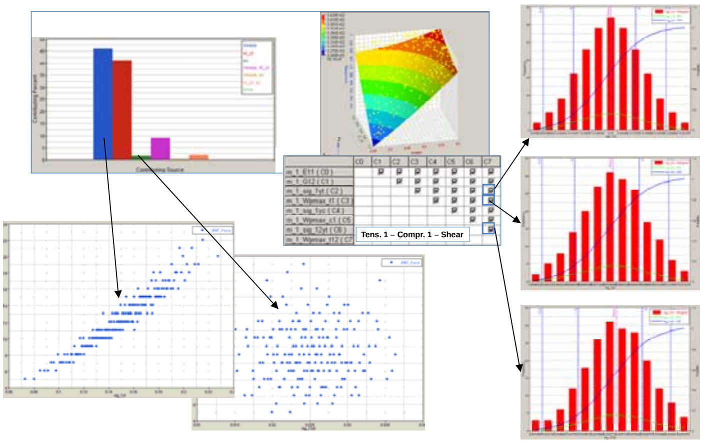

Fig. 8: post-processing phase: DOE results analysis.

From DOE results a small group of "sensible" parameters have been determined and to those ones a statistical distribution has been assigned according to experimental tests and manufacturers hints. (Example of effect and interaction of maximum tensile stress in direction 1, maximum tensile strain energy in direction 1 and maximum shear stress is shown in the figure on the right).

As a conclusion, the in-depth analysis of the DOE plans results allowed to better understand the mutual relationship among the different parameters characterizing the numerical cards defining the mechanical behaviour of composite materials within commercial FE codes. This knowledge translates in an increased confidence in the results. In this sense we claim the statistical method here presented is a much more robust approach compared to the old deterministic approach. This expertise, of maximum interest, is the necessary basis for any further step, as explained in the following paragraph.

Lessons learned and future work

The project performed within the SHAPE pilot programme allowed us to greatly extend the preliminary work made inside the company, extending its field of application to more industrially-relevant problems and confirming tendencies and mutual relationships among parameters.

It is clear to us that, without such a massive use of computation, it would not have been possible to achieve the confidence now we have in our approach. Due to the limited extent in time and effort of the SHAPE project further enabling projects will probably be necessary to arrive at a production level. As an example, approaching the end of this pilot project the partners submitted a proposal to the second call of the FP7 Fortissimo Project. The main limitation of the tool developed within this SHAPE Pilot is that at the moment is usable only by experts.

In our plans, this piece of software will be able to set the statistical approach as a possible one through a guided procedure and a massive use of HPC, whose resources are getting more and more available to industry. The competitive advantage we envisage in developing this procedure and releasing it on the market is of the greatest interest.

This SHAPE Pilot project run smoothly, with the only remark that the allowed computing resources budget was a bit limited, even though sufficient for the purposes of a proof-of-concept. However, the proactive help of CINECA gave to the project the possibility to reach its targets in time and with results of high quality.

Moving from the particular of our project to broader considerations, a strong limitation for this kind of analysis, especially when SMEs are involved, comes from the use of commercial software suites, involving very high license costs. PRACE-enabled industrial projects could be important either in increasing acceptance of open-source software by the large companies for which engineering SMEs in the automotive sector work, or in pushing ISVs to embrace more friendly (pay-per-use) licensing models.

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