Numerical-Experimental Correlation of Mechanical Tests on Fiber-Reinforced Polyamide Composites

Alfonso Molaro[1], Maria Sofia Lanzillo[1], Francesco Zimbardi[1], Andrea Causa[1], Beniamino Villacci[1]

[1]SAPA s.r.l., Via Appia Est 1, 82011 Arpaia, Italy

Abstract. This work (supported by the APPS4SAFETY financed project) presents an experimental and numerical study of the mechanical behavior of polyamide 66 (PA66) filled with short glass fibers (GF) and short carbon fibers (CF), which are appealing materials for the development of active automobile safety devices. As the latter need to be validated through numerical simulations of crash tests, the study described herein is aimed at the determination of the elements that define the LS-DYNA® cards for the PA66-GF and PA66-CF composites. Firstly, such fiber-reinforced materials have been thoroughly characterized by performing tensile tests on specimens cut from injection-molded panels at different orientations relative to the preferential fiber direction (0°, 45° and 90°). Secondly, representative simulations of the experimental mechanical tests have been performed by developing in LS-DYNA® two- and three-dimensional models of the specimens and subjecting them to quasi-static tensile loads. The material model used to describe the behavior of short fiber-reinforced thermoplastics is *MAT_NONLINEAR_ORTHOTROPIC (*MAT_040). Finally, the simulated stress-strain curves have been calibrated with the experimental ones; namely, the parameters of the numerical curves have been optimized to obtain a good interpolation of the experimental results. For both the PA66-GF and PA66-CF composites, two-dimensional modeling has provided a better correlation between numerical and experimental data in comparison with the three-dimensional one.

1 Introduction

The small overlap frontal crash test was introduced in 2012 by the Insurance Institute for Highway Safety (IIHS) to evaluate the crashworthiness of a vehicle and drive significant improvements in frontal crash protection. Such test is designed to replicate what happens when the front corner of a vehicle collides with another vehicle or an object and challenges several passive safety components (for instance seatbelts, airbags and bumpers) that help reduce the effects of an accident for the occupants [1]. Some recent solutions aimed at the improvement of vehicle crashworthiness envisage the modification of the trajectory of the vehicle and, in turn, the dynamics of the accident through appropriate devices, allowing to limit the forces on the cabin and protect the passengers. For this purpose, the design of components with a high impact resistance, able to transfer the stresses to the surrounding structures, is strictly required. Among the materials of potential interest for the production of parts of these components, composites stand out for their greater capacity to absorb energy compared to metals, mainly due to the different modes of failure that govern energy absorption [2]. In particular, fiber-reinforced polyamides are appealing formulations for their outstanding thermo-mechanical and impact performances [3].
The validation of analytical and numerical models for accurate simulations of structural response to crash impact represents a crucial aspect in crashworthiness research. Indeed, such tools are necessary for the designer to study the response of a specific structure to dynamic crash loads, to predict the global response to impact, to estimate the probability of injury and to evaluate numerous crash scenarios, which would not be economically feasible with full-scale crash testing [2]. In the view of these considerations, it is easy to figure out that one of the steps to perform to validate new concepts for frontal crash protection is the simulation of the small overlap frontal test through computer models. Since car crash is considerable as a transient dynamic event and a nonlinear explicit code is required to perform the aforementioned analyses, LS-DYNA® is a software package that can be used successfully employed for this purpose.
This work is focused on two materials of potential interest for the design of car safety components, based on polyamide 66 (PA66) filled with short glass fibers (GF) and short carbon fibers (CF) respectively. A thorough mechanical characterization of these materials has been firstly performed in order to determine the parameters that constitute the LS-DYNA® material cards. Secondly, appropriate material models for the PA66-GF and PA66-CF formulations have been selected in the LS-DYNA® library and their validity has been checked by setting up simulations of the mechanical tests and finally comparing the experimental and numerical results. The activity described so far has been supported

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by the financed project "APPS4SAFETY - Active Preventive Passive Solutions for Safety: an integrated approach to develop safer cars" and will serve to perform further simulations to validate the structural response of components for frontal protection made of fiber-reinforced PA66.

2 Experimental study

2.1 Sample preparation and characterization

Two kinds of commercially available PA66-based formulations were used in this study: a GF-filled PA66 (RADILON A LRV600W, density ρ = 1700 kg m^{-3}) and a CF-filled PA66 (RADILON A CF400, ρ = 1320 kg m^{-3}) having filler weight contents of 60 and 40% respectively. Both the materials were supplied by Radici Group (Italy).
GF-PA66 and CF-PA66 plates having dimensions of 300×300×3 mm^3 were produced by means of a 550 ton injection molding machine (OIMA, Italy), the melt and mold temperatures being set to 290 and 90 °C respectively. The materials were dried at 30 °C for 3 h prior to molding.
Aiming to prepare specimens for the mechanical tests, the injection-molded plaques were trimmed using a laboratory milling cutter. Due to the orthotropic connotation of the materials, the specimens were cut in three different ways: at 0° (longitudinal), 45° (transverse) and 90° (perpendicular) relative to the flow-induced fiber direction, as shown in Fig. 1.

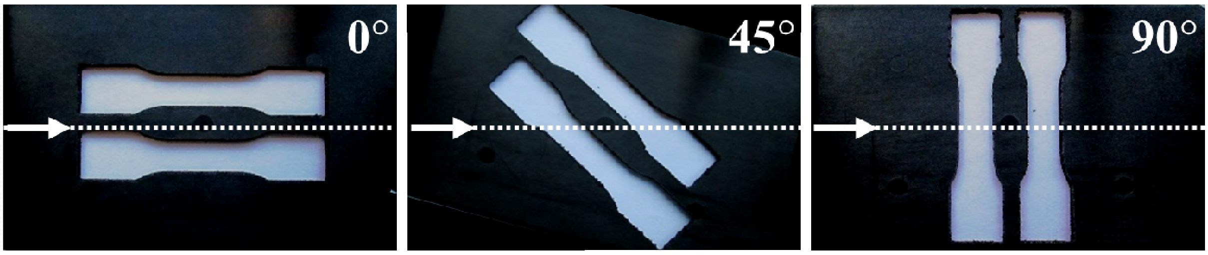

Fig.1: Specimen cutting orientations relative to the flow-induced fiber direction (arrows).

The mechanical properties of the samples were determined through tensile tests performed at room temperature and humidity, in accordance with ASTM test method D3039. The specimens (nominal size 180×25×3 mm^3) were tested using a Zwick/Roell Z250 testing machine, equipped with a 250 kN load cell. Strain gauges were applied on the specimens in order to detect their deformation in the direction of load application. The speed set for the test was 2 mm min-1 until break, and the stress-strain curves, Young moduli, tensile strengths and elongations at break were recorded. The reported data are the average values of the results of 5 tests per sample and orientation.

2.2 Results and discussion

Tables 1 and 2 report the results of the tensile tests in terms of average Young modulus, tensile strength and elongation at break for each material and fiber orientation relative to the direction of the applied load.

Orientation	E [GPa]	σ_b [MPa]	ε_b [%]
0°	21.1 ± 0.6	174 ± 9	1.1 ± 0.1
45°	9.9 ± 0.1	103 ± 12	1.6 ± 0.4
90°	12.9 ± 0.1	89 ± 34	1.0 ± 0.1

Table 1: Mechanical properties of PA66-GF for different fiber orientations.

Orientation	E [GPa]	σ_b [MPa]	ε_b [%]
0°	24.5 ± 0.9	155 ± 4	0.9 ± 0.1
45°	11.1 ± 0.2	110 ± 12	1.4 ± 0.4
90°	12.6 ± 0.1	72 ± 1	0.6 ± 0.1

Table 2: Mechanical properties of PA66-CF for different fiber orientations.

Representative stress-strain curves for each material and fiber orientation are shown in Fig. 2 (PA66-GF) and Fig. 3 (PA66-CF).

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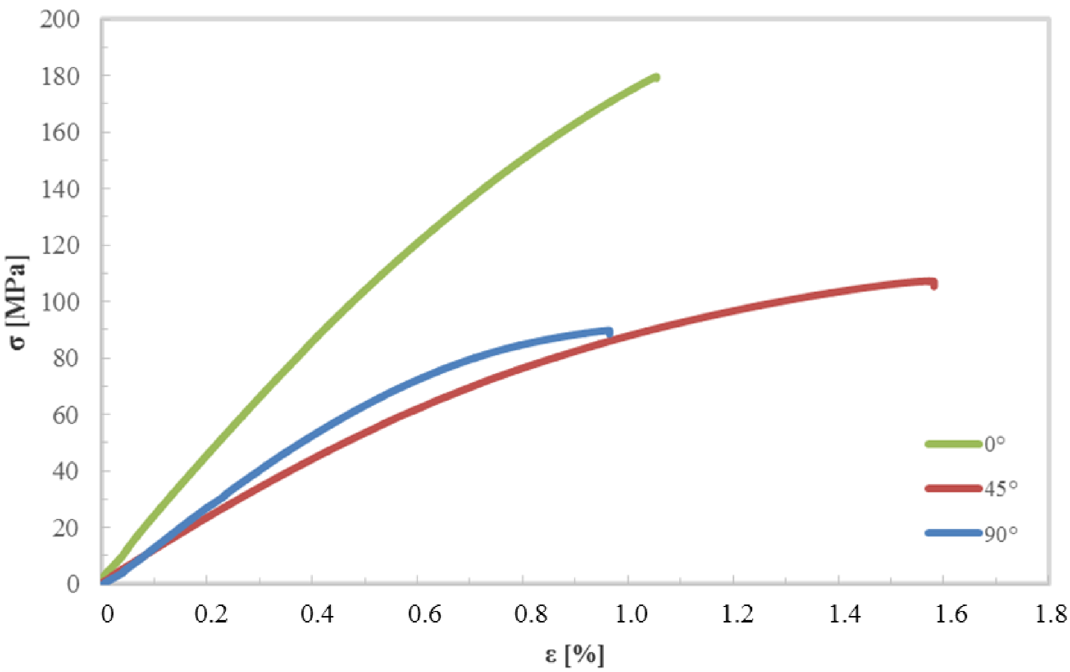

Fig.2: Variation of stress-strain curves with fiber orientation for the PA66-GF specimens

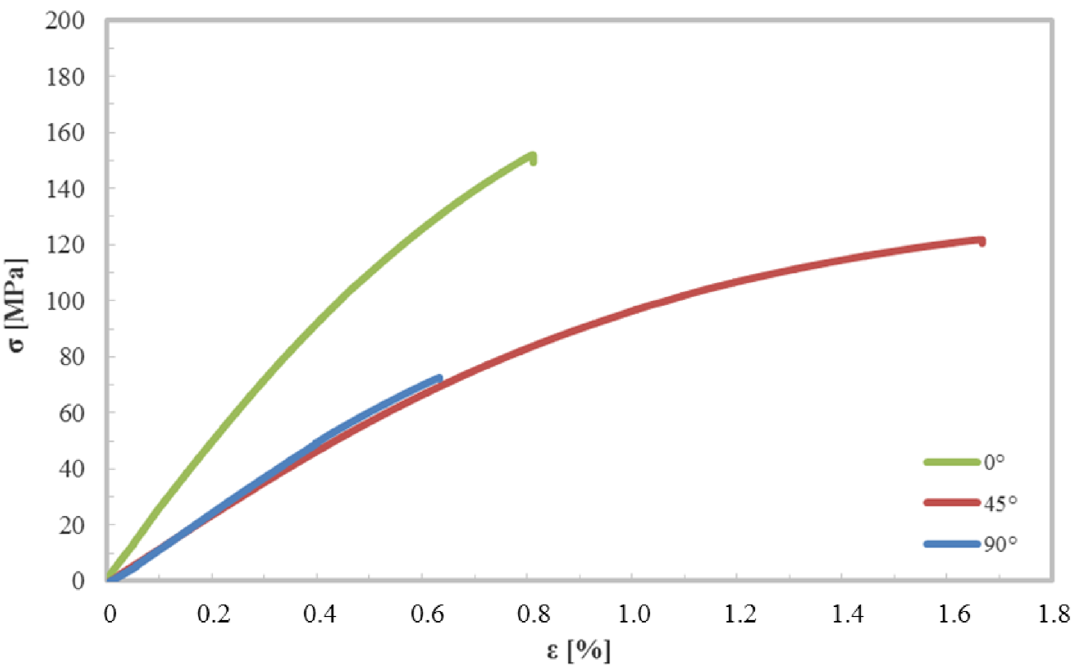

Fig.3: Variation of stress-strain curves with fiber orientation for the PA66-CF specimens

The results clearly show the strong anisotropy effect induced by the injection molding process. In fact, both materials exhibit the highest modulus and tensile strength in the in-flow direction, and the highest elongation at break in 45° direction. In the perpendicular-to-flow direction, the modulus and tensile strength are about 50% lower compared with the in-flow direction and the elongation at break decreases relative to the 45° direction by about 37% in the PA66-GF sample and 62% in the PA66-CF one. Similar results have been recently reported in literature studies for polyamides reinforced with either short glass fibers [4,5] or short carbon fibers [6]. The higher strain at break in 45° direction compared to 0° and 45° is due to the strain limit of the fibers. In the longitudinal direction, the fibers are highly aligned with loading direction, hence the low straining capacity of the fibers results in a low ductility of the composite. On the other hand, matrix straining and the interfacial properties are dominant in 45° and 90° direction. The great ductility of the samples in the 45° direction is ascribable

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to the fact that the yielded matrix has more space to elongate between fibers and in the loading direction.

3 Numerical analyses

3.1 Prefatory notes

After performing the mechanical characterization of the materials, numerical analyses representative of the experimental tensile tests have been conducted. LS-DYNA® has been used for both creating the finite-element model of the specimens and performing the test simulations, where a quasi-static load has been applied.
Various mathematical models that describe the mechanical behavior of fiber-reinforced composite materials with polymeric matrices are available in LS-DYNA® database. Among them there are:
- the Cowper-Symonds model;
- the Jones model;
- the Johnson-Cook model.

The most interesting comparison is that between the predictions of the models developed by Cowper and Symonds and by Johnson and Cook. The Jones model, in fact, is scarcely innovative and exhibits several similarities with the Cowper-Symonds model.
The model by Johnson and cook is simpler and allows a faster convergence in determining the values of the necessary material parameters, whereas the Cowper-Symonds model provides a more accurate interpretation of the experimental results, especially for high strain rates (~ 10^3 s^{-1}). The main drawback of the Cowper-Symonds model is represented by the fact that, above all in the case of metals, neglecting the temperature influence on the evolution of a dynamic process does not allow to correctly interpret all the factors that define the mechanical response of the material. Nevertheless, the Cowper-Symonds model is extensively employed due to the good correspondence between analytical data and experimental results.
Other material models enable to simulate the mechanical behavior of anisotropic fiber-reinforced components with a good level of approximation. Specifically, *MAT_NONLINEAR_ORTHOTROPIC (*MAT_040) envisages the introduction of experimental stress and strain values as references.

3.2 Steps of the activity

As previously pointed out, the numerical analyses have been performed using the explicit LS-DYNA® finite element code. It is particularly suitable for static and dynamic nonlinear analyses of mechanical structures and for the investigation of phenomena that rapidly evolve during time, like car crashes.
Numerical analyses consist of three essential phases: pre-processing (geometry acquisition, finite element modeling and model transfer to the solver), processing (numerical calculus) and post-processing (numerical analysis and calibration of the model through experimental and literature data).

3.2.1 Pre-processing

The finite element modeling of elasto-plastic materials is a continuously evolving field, where the main complications arise from the marked nonlinear mechanical features of such materials. Due to the strong dependence of the mechanical properties upon strain rate, a thorough experimental characterization is strongly required in order to satisfactorily model the behavior of a plastic material. A large set of numerical analyses is often necessary when investigating the influence of the strain rate on the mechanical behavior of the aforementioned materials, except in the case of relatively low deformation rates (like in the present work).
The geometry of the specimens has been modeled starting from dimensional analyses. Fig. 4 and Fig. 5 show the two- and three-dimensional models used for the numerical simulations.

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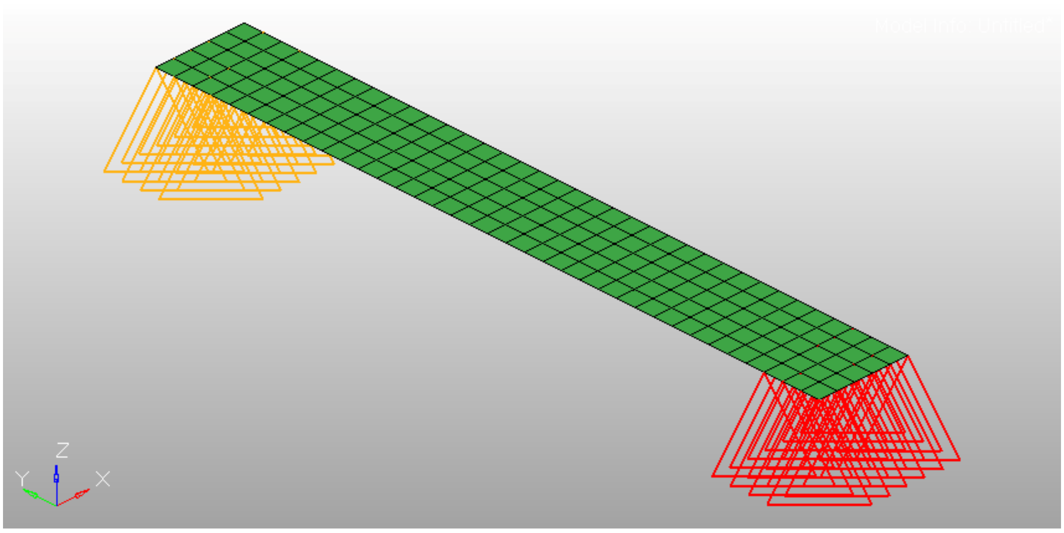

Fig.4: Two-dimensional numerical modeling of the tensile test

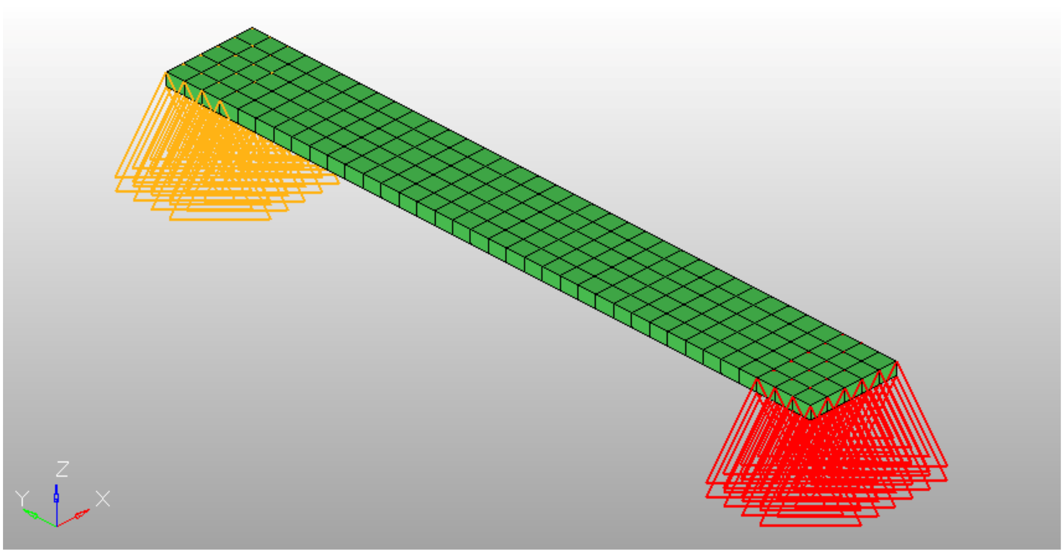

Fig.5: Three-dimensional numerical modeling of the tensile test

In order to take into account the anisotropy of the material, the *MAT_NONLINEAR_ORTHOTROPIC (*MAT_040) model, mentioned in Section 3.1, has been used. The coefficients and the stress-strain curves for this model have been inferred from the experimental tests.
The boundary conditions have been applied according to the specifications of ASTM D3039, i.e. the standard for the tensile tests used in the experimental activity. Specifically, one of the end of the specimen has been fully constrained (3 and 6 degrees of freedom blocked in the two- and three-dimensional representations, respectively), while the other one has been fully constrained except in the direction of load application, along which a displacement with velocity 2 mm/s has been imposed.
Two types of modeling have been adopted. The first solution envisages 4-node SHELL plane elements with 6 degrees of freedom (3 translations and 3 rotations) per node. In the second solution, 8-node hexahedron elements with 3 degrees of freedom per node have been employed. The two- and three-dimensional models include 222 and 444 nodes respectively, and both have 180 elements. The characteristic element dimension is 5 mm for both the models, the aspect ratio (between the lengths of the long and short edges) is 1.00 for the two-dimensional model and 1.56 for the three-dimensional one. In the latter, a single element is found in the thickness of the specimen.
The discretization of the two- and three-dimensional models of the specimens is illustrated in Fig. 6 and Fig. 7.

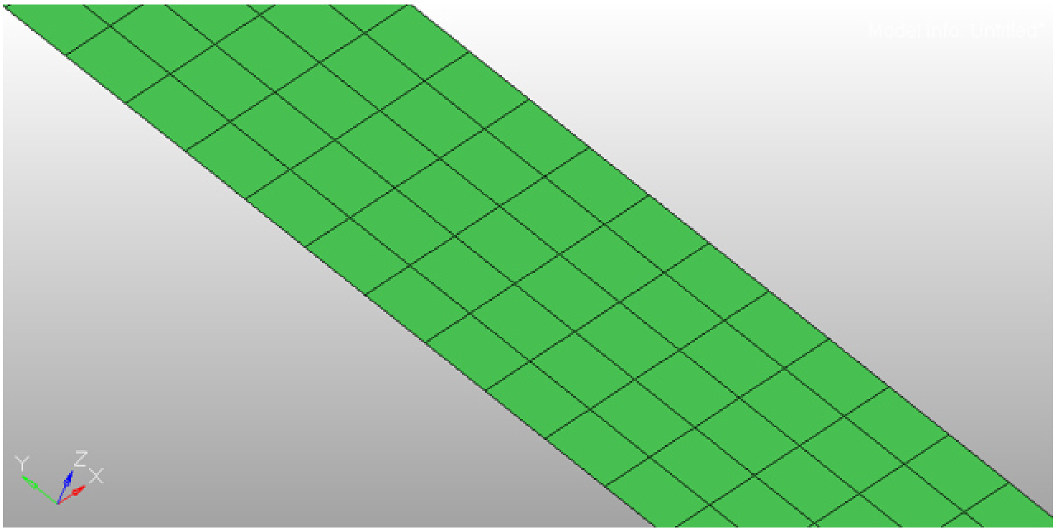

Fig.6: Two-dimensional discretization of the specimen for tensile tests

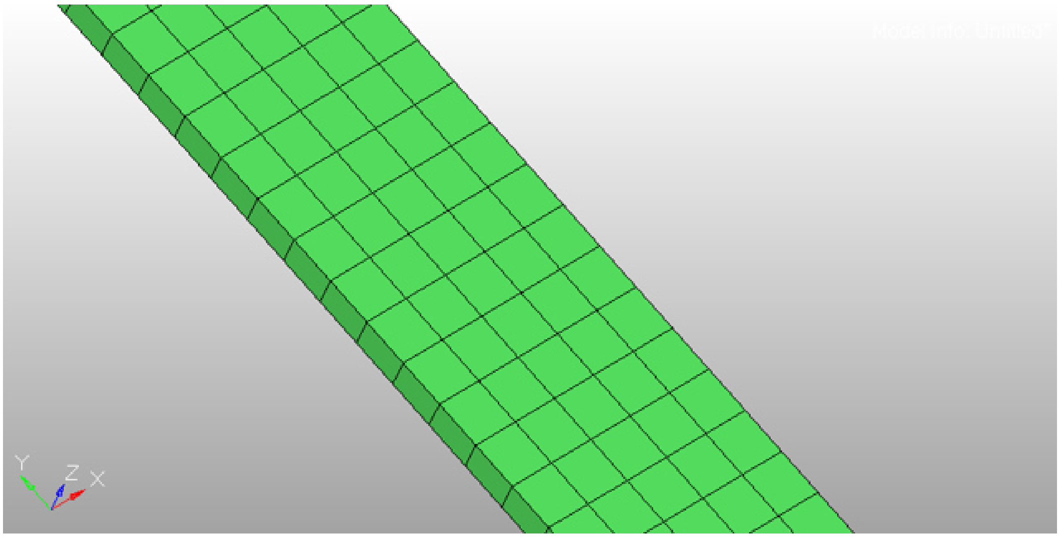

Fig.7: Three-dimensional discretization of the specimen for tensile tests

The structural parameters to introduce into the selected material model have been deduced from the experimental results. In particular, the following characteristics have been determined:
- Young moduli along the directions of the reference axes;
- the Poisson ratios;
- experimental stress-strain curves along the load direction and the perpendicular directions;
- elongation at break.

3.2.2 Processing and post-processing

After completing the numerical modeling step, the simulations have been launched. At this stage, on the basis of the imposed boundary conditions, the software determines the displacement field in time-domain for explicit analyses. Workstations with 32 physical cores and 128 GB RAM have been employed to perform the analyses, the simulation time being about 8 minutes.
At the end of the simulation, the numerical stress and strain data and stress-strain curves have been extrapolated in order to perform the subsequent comparison with the experimental results.
A qualitative tension mapping obtained from the simulation is shown in Fig. 8.

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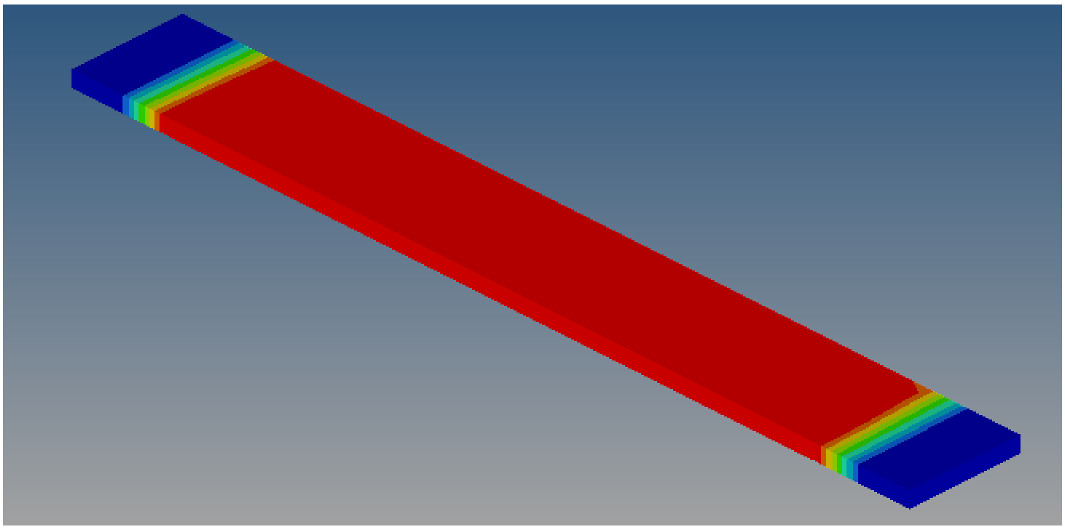

Fig.8: Three-dimensional simulation of the tensile test: qualitative tension map

4 Numerical-experimental correlation

Fig. 9 and Fig. 10 show the experimental and numerical results for PA66-GF and PA66-CF. For both the materials, the numerical stress and strain results are in good agreement with the experimental ones. In particular, the two-dimensional model proves to be very accurate in reproducing the mechanical behavior of composites made of polyamide and short reinforcing fibers. Indeed, the stress-strain curves obtained from the simulations retrace the experimental ones up to the fracture of the specimen, with minor differences in the values of elongation at break for the PA66-GF sample. On the other hand, the curves obtained from the three-dimensional model exhibit significant fluctuations starting from intermediate strain values (0.9% for the PA66-GF sample, 0.7% for the PA66-CF one) even if the general trend does not significantly deviate from the results of the tensile tests.

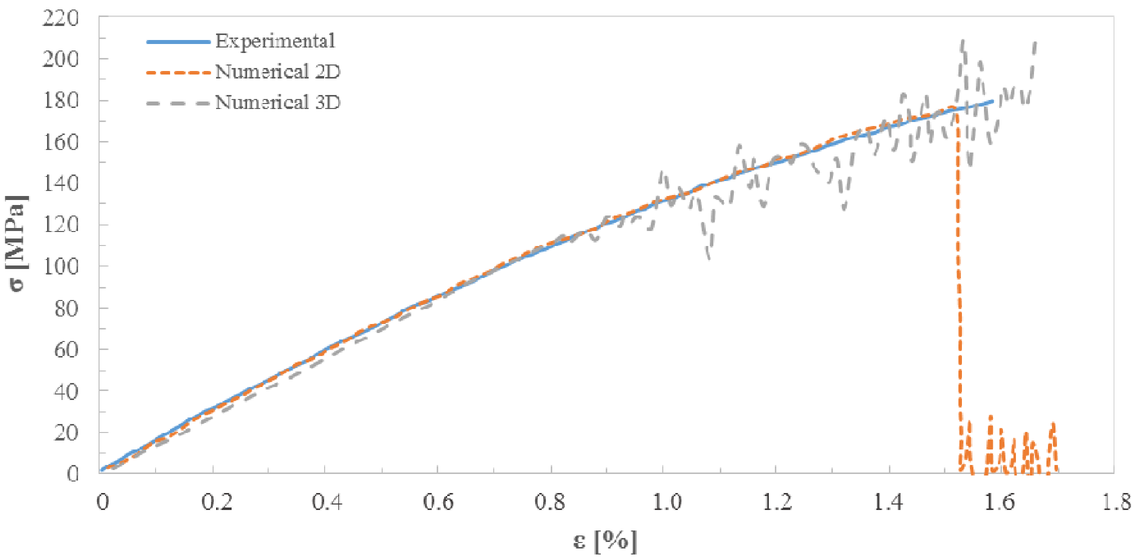

Fig.9: Comparison between experimental and numerical data for the PA66-GF sample

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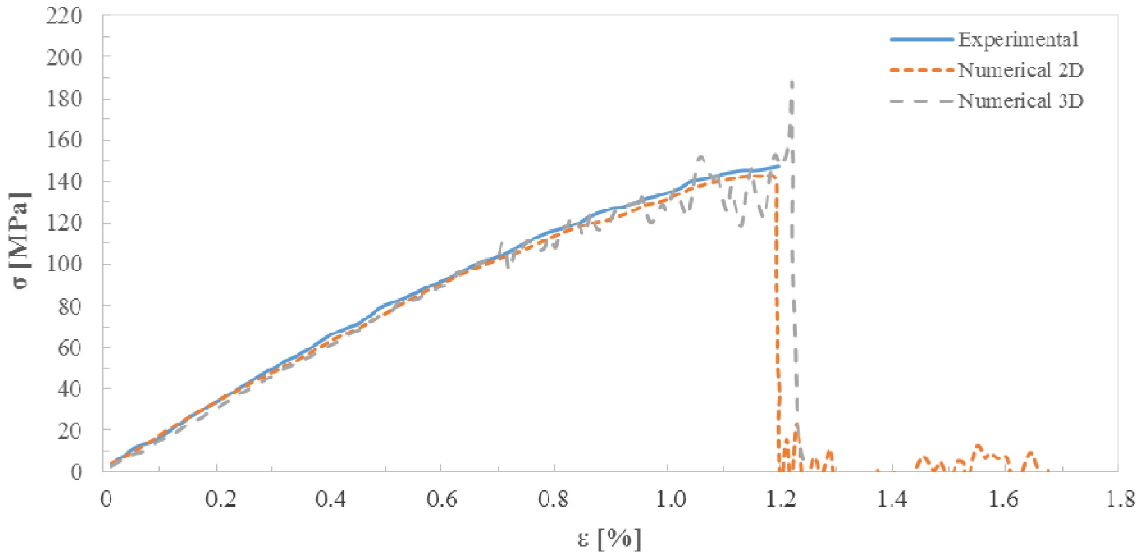

Fig.10: Comparison between experimental and numerical data for the PA66-CF sample

The output of the numerical-experimental correlation described so far are the material cards for the PA66-GF and PA66-CF composites, reported in Fig. 11 and Fig. 12 together with the load curves for the 0° and 90° directions (note that there the strain is expressed in µm/m, the stress in MPa). Directions 0°, 90° and 45° are respectively designed A, B and C in the card. EA, EB and EC are the corresponding Young moduli and PRBA, PRCA and PRCB the Poisson ratios.

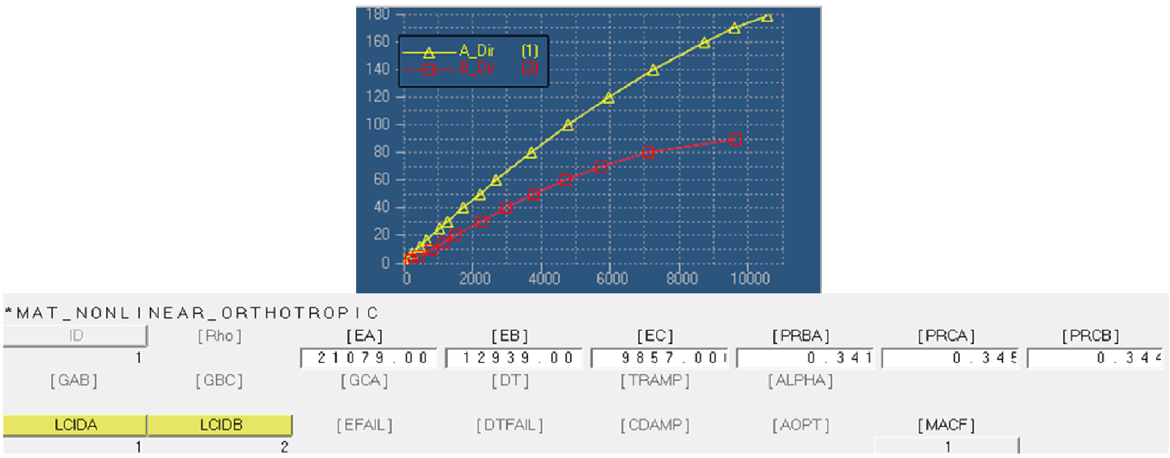

Fig.11: Comparison between experimental and numerical data for the PA66-GF sample

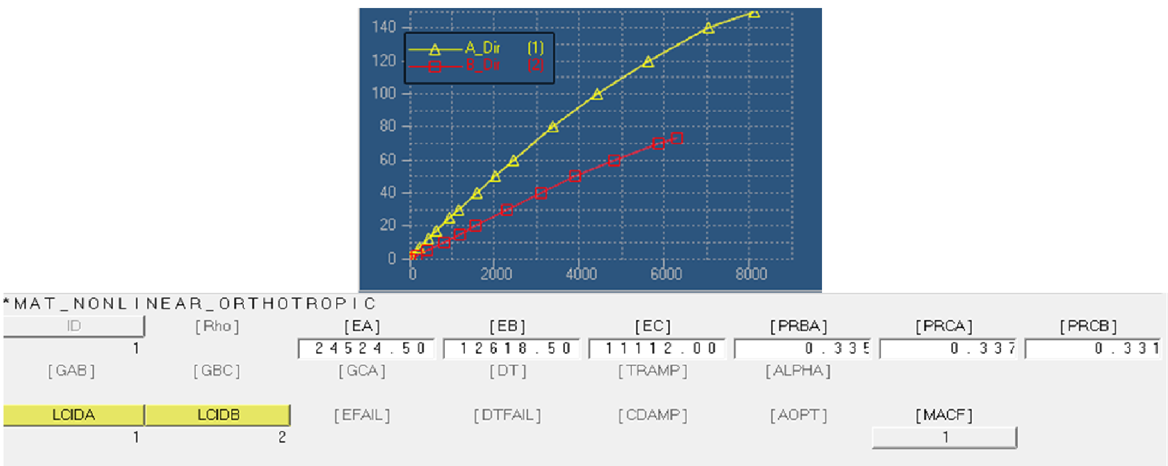

Fig.12: Comparison between experimental and numerical data for the PA66-CF sample

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5 Summary

The objective of this work is the definition of the LS-DYNA® material cards for two composites with polyamide matrix and two different reinforcing fillers: short glass fibers and short carbon fibers. These materials are promising for the design of automotive safety components (especially for frontal crash protection) due to their good mechanical performances. In order to determine the parameters that define the LS-DYNA® cards for the two composite materials, the mechanical behavior of the latter has been thoroughly investigated by means of tensile tests performed on injection-molded specimens. Three directions of load applications have been considered: 0°, 45° and 90° relative to the in-flow direction (which correspond to the preferential orientation of the fiber). The experimental results have then been compared with the outputs of numerical simulations of the tensile test: specifically, two- and three-dimensional models of the specimens have been developed and subjected to quasi-static loads. The material model selected, that is *MAT_NONLINEAR_ORTHOTROPIC (*MAT_040 in the LS-DYNA® database), has proven to satisfactorily describe the mechanical behavior of thermoplastic materials reinforced with glass fibers. For both the composites, two-dimensional modeling has provided a better numerical-experimental correlation compared with the three-dimensional one. Indeed, the stress-strain curves obtained from the two-dimensional model exactly retrace the experimental ones, whereas the diagrams inferred from the simulations on the three-dimensional model exhibit some fluctuations at relatively high strains.

The whole activity has been supported by the financed project “APPS4SAFETY - Active Preventive Passive Solutions for Safety: an integrated approach to develop safer cars”.

6 Literature

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