Simulating anisotropy with Ls-dyna in glass-reinforced, polypropylene-based components

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Summary:

Glass-fiber-reinforced polypropylene (GF PP) materials are increasingly being used by customers to replace metal and engineering polymers in structural automotive applications. Like all glass-fiber-reinforced thermoplastics, GF PP products can show anisotropy caused by fiber orientation that is induced by the injection process. Taking into account fiber orientation in the simulations enables designers to improve the accuracy of the analyses. This can help prevent arbitrary choices and assumptions when setting material parameters, which become mandatory when an isotropic material law is used.

The method proposed in this paper takes advantage of the availability within Ls-dyna of an anisotropic material law (MAT_103), which allows simplified modeling to address critical issues. This law was not developed to address the problem discussed here.

Therefore, this paper illustrates a simplified approach. The presence of glass reinforced fibers is taken into account by running a mold-filling analysis, and then transferring the material flow orientation in to the structural simulation as a material angle. The dependence of the material failure strain on the material orientation can be also easily modeled through a user subroutine. Finally, the approach only requires simple material data based on basic tensile tests; the material law parameters are then identified through optimization techniques.

Although this approach is based on some simplifying assumptions, its application is quick and can help the designer obtain more accurate results with respect to the traditional isotropic approach. A selection of validation tests is then proposed that show reliable predictions using limited additional computational effort.

Keywords:

Anisotropy, Fiber Reinforced Polymers, Crash Simulation, Impact, Material Modeling, Material Characterization, Parameter identification

1 Introduction

Polymer matrix composites are increasingly used in structural applications for their light weight and durability. However, the numerical modeling of these materials poses several challenges. The first challenge is the highly anisotropic nature of their behavior.
Most of the polymer matrices reinforced with glass fibers have a non linear behavior under mechanical loading; therefore, linear models frequently found in the literature and widely available in F.E. (Finite Element) codes are not of practical use.
In recent years, many efforts have been dedicated to providing the designer with computer codes containing comprehensive constitutive equations, sometimes embodying several state variables and the most general mathematical forms. Although this approach may be appropriate in the final stages of design, it may be too complicated for many applications, particularly in the early stages of the design.
In this paper, a simplified approach is propounded.
The basic idea is to use a material law that already exists in a commercial F.E. code, which needs to be anisotropic, non-linear and strain-rate dependent, possibly with a failure criterion that depends on the material orientation and strain rate.
A first requirement is to have the possibility of including some information extracted from the process used for making the polymeric part, because the anisotropy for these materials is induced by the manufacturing process. This requirement will be discussed later in the paper. Such information will be translated into a material orientation or material angle
Secondly, it is important that a computational tool of practical use avoid putting the designer in conflict with the experimenter, if at all possible. In other words, the computational law must not require complex experimental tests for its parameters assessments. Following this guideline is not easily accomplished when dealing with anisotropy. We will show that this problem can be efficiently solved by using a reverse engineering approach, coupled with appropriate optimization methods. The ideas highlighted here can be suitably developed using Ls-dyna, which makes several anisotropic laws available.
We found the law called “MAT_ANISOTROPIC_VISCOELASTIC” (labeled as *MAT_103) to be one of the best respondents to the criteria above. This law was not developed to specifically address the problem discussed here. This paper reports the main activity made for tuning this law for our purposes, in particular for interfacing the material law with the experimental data available and with the input data from process simulation.

2 Anisotropy: mechanical properties of glass reinforced PP

This section provides the interested reader with some “physical” aspects of Short Glass-Fiber-reinforced Polypropylene (SGF-PP). All of the examples reported here are taken from materials available within the wide-range product portfolio of LyondellBasell.
For the materials listed on table 1, we report mechanical properties measured on specimens cut from an injected plaque either along the direction parallel or perpendicular with respect to the material flow. The mechanical properties measured are the elastic modulus and maximum stress. For each property, we report the ratio between the values measured along the two directions considered.

Material type	*Transv/Long Moduli ratio*	*Transv/Long Max stress ratio*
40% SGF-PP homopolymer	0.5	0.56
30% SGF-PP homopolymer	0.63	0.67
10% SGF-PP homopolymer	0.86	0.82
25% SGF-PP Soft PP	0.57	0.68
Impact modified PP/Talc	0.81	0.83
Unfilled PP copolymer	0.93	0.93

Table 1: Typical ratio longitudinal/ transverse properties of some PP-based materials measured on a plaque.

It is clear from Table 1 that the anisotropic behavior that characterizes almost all PP-based materials is based significantly on the type and amount of filler or reinforcement. Glass-fiber-reinforced materials are those that show the most pronounced anisotropy.
These conclusions can also be extended to the non-linear and plastic region. The example in Figure 1 shows various SGF-reinforced materials with different percentages of the reinforcement and different

matrices. The graph in Figure 1 also shows that the elongation at break can be affected by the material orientation.
In a multi-phase material such as SGF-PP, the mechanical properties depend on the constitutive properties of the base materials and the composite morphology, i.e., the weight fraction, length, diameter and orientation of the fibers. These properties are induced by material processing, as in the case of injection molding. Here, a classical skin-core structure is observed and, depending on the thickness, can be more or less pronounced. Along the material thickness, a central portion or "core", is characterized by fiber orientations perpendicular to the flow, and a lateral portion is characterized by fiber orientations parallel to the flow .[3].
As an example, in Figure 2, two images of the rupture surface of two specimens cut from an injection-molded plaque of a 40% SGF-PP homopolymer are displayed. Here, the two specimens are taken from the plaque from the positions depicted on fig. 2, i.e. one parallel and one perpendicular with respect to the polymer flow direction. Accordingly, the typical core-skin structure, which is clearly visible, shows fiber orientations 90° rotated from one case to the other. Here, the relative skin-to-core thickness ratio can be qualitatively assessed, suggesting the presence of a narrow core in which the fibers are well oriented, and a wider skin with less pronounced orientations.

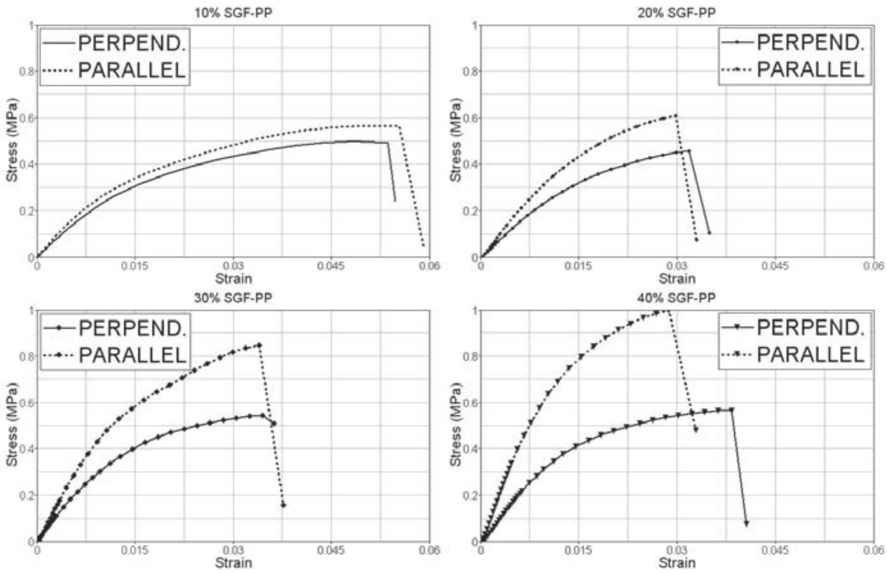


Fig. 1: SGF-PP curves stress-strain, measured on specimens cut from a plaque in the direction perpendicular and parallel to the flow lines. Examples include four different fiber percentages (10%, 20%, 30%, 40%). The stress values are normalized to the maximum value measured.

In each layer along the thickness, the fiber direction, the percentage of alignment and theoretically the fiber amount may vary. The combination of the properties of all the layers determines the properties of the whole assembly.
The fiber orientations can be predicted through numerical tools. In commercial codes, the orientations are usually governed by the Folgar-Tucker equation [6]. This equation requires the user to introduce coefficients that depend on specific material and fiber geometry. We noticed that these coefficients have a strong influence on the fiber orientations through the layers and consequently on the final material properties. Therefore, they need to be tuned to the specific application [12]. This might be the root of possible uncertainties in the local material properties.

3 Simulating an anisotropic material

In this section, the computational tools required to model the materials behavior will be discussed, as well as other options that may be available to the designer.

At an industrial level, design departments have historically followed a method based on isotropic models: this means that the directional dependency of the material properties is neglected, and "ad hoc" material properties are used dependent on the problem studied. As an example, in the case of

parts that clearly show a preferential flow orientation, and are loaded mainly along that direction, the mechanical properties measured along that direction are profitably used. Otherwise, a worst-case condition can be used, with properties measured along the most penalizing condition. In any case, this provides engineers with a working knowledge of the problem on which to base the design.
Much more detailed is the micro-modeling approach, with direct FE computation of the boundary-value problem at each representative volume element; however, due to its computational cost, it cannot be considered a resource for designing an industrial component.

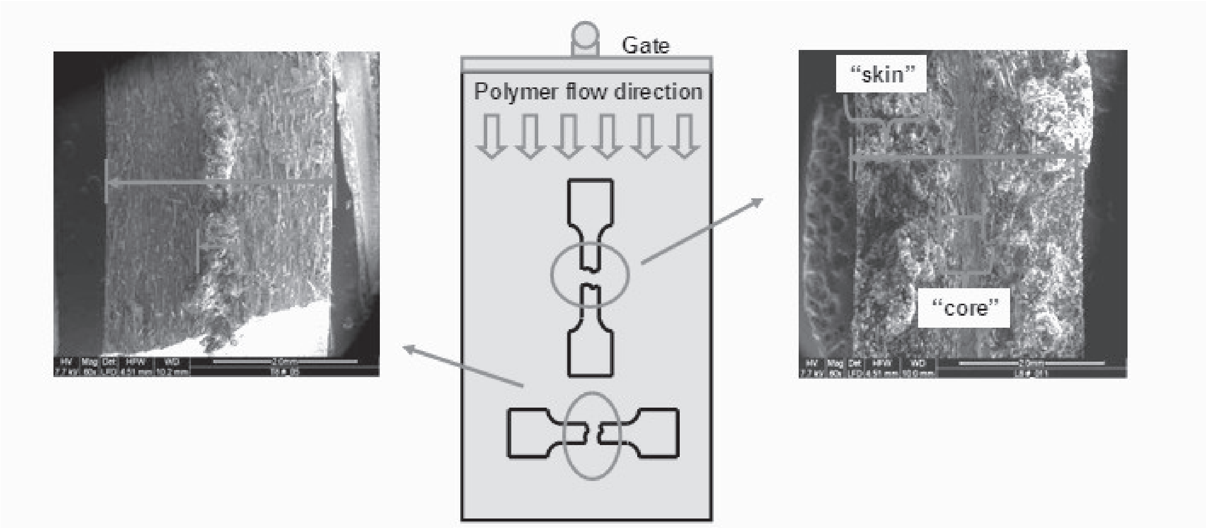


Fig. 2: Rupture surface of broken tensile specimen cut from plaque (SEM images, material: 40% GF PP homopolymer)

An intermediate approach is to utilize two-scale models, with a macro-scale associated to the part and a micro-scale associated to the material microstructure. The transition between the two scales can be accomplished through a homogenization process. In this case, fiber content, geometry and fiber distribution, together with the matrix properties, are the required parameters [4].

However, the approach that we propose takes advantage of anisotropic material laws already available in Ls-dyna to provide a tool for engineering design, improving the quality and accuracy of the FE prediction traditionally achieved by isotropic modeling, with limited additional computational effort.
We chose the law *MAT_ANISOTROPIC_VISCOELASTIC (MAT_103) because it complies with our original requirements, with the exception that it is isotropic in the elastic phase. Its influence can be reduced by selecting an appropriately low value for the yield point.

4 Adapting Ls-dyna material law

In this section we examine the requirements of the chosen material law, aiming to verify how it can be adapted for the purposes of our analysis.
We will focus our attention on the three main steps executed for adapting the existing law to our purposes, regarding the interface with mold-filling simulation, the procedures for material testing and the identification of the material parameters. Finally, some considerations about failure modeling will be made.

4.1 Local orientation and interface with the process-simulation

First of all the material law must render the introduction of a local material orientation feasible.
In this regard, MAT_103 allows the introduction of a material local coordinate system, to which the user's manuals refer as the **a-b-c** system [10]. For shell elements, the **a** axis of the element can be defined by the cross product of an user defined vector with element normal (using the option

AOPT=3), **c** is coincident with the element normal, **b** is defined through the cross product between **a** and **c**.
Then, the material axes are rotated by an element angle to get the reference direction for the element (using *ELEMENT_SHELL_BETA). Accordingly, the element angle (variable PSI) must be introduced for each element to define the material directions.
This is the way chosen to transfer to the impact simulation the process-related information.
In fact, one of the developments of the present work has been setting an interface to derive the material direction, via the element angle, from the process simulation. Thus, a dedicated interface from the code Moldflow (used for moldfilling analysis) to Ls-dyna has been conceived, written and tested.
The key point of this process is to select which mold-filling simulation output will be transferred as input to the structural analysis. A variable representing element by element the flow direction in the mold has been chosen. This choice dictates which experimental data are needed and gives implicit directions about the testing procedure, which will be addressed in the following paragraphs.
For The computational meshes for mold-filling and structural analyses respond to different criteria; a rough algorithm to map the information from the tri-mesh used for the process simulation to the quad-mesh used for the structural simulation has been implemented. In this simple procedure, the original mesh is build with "QUAD" shell elements, each of them being properly divided through its diagonal in two "children" "TRI" elements for the mold-filling simulation; the resulting vectors expressing the material angle of each of the child elements are then recombined to assign the material angle to the original "parent" QUAD element.

4.2 Dedicated Measurement of Mechanical Properties

Next, we will describe the method proposed for measuring the mechanical properties and highlight why it is suitable and specifically tuned for the comprehensive approach for anisotropic material modeling.
The procedure used for material characterization, with particular reference to the method for obtaining the specimens to be tested, is one key ingredient for this approach. This is the standard testing method in LyondellBasell that proved to be suitable for this application.
Samples should have fiber orientations as similar as possible to those existing in the real components. For this to occur, specimens are cut from injection-molded plaques; typically 150 x 250 mm with a thickness of about 3.15 mm. The T-bar specimens used are reported in fig. 3.

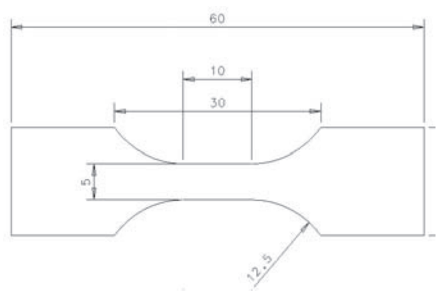


Fig. 3 T-bar specimen used for material characterization

By so doing, it is possible to cut specimens along any desired direction with respect to the injection flow. The material orientation in the plaque is similar to the one that exists in the real components. For instance, in injection-molded specimens, the orientation is emphasized as in the narrow sections of T-bars
As an example, on Table 2 we report the tensile moduli measured on two materials, respectively a 20% SGF-PP and a 40% SGF-PP, where the measurements are reported for both molded T-bars and T-bars cut from plaques parallel and perpendicular with respect to the flow lines. The higher moduli measured on the molded T-bars indicate a higher fiber average alignment.
The choice of the location on the plaque where the specimens need to be cut from is also relevant. As said, the specimens are cut according to two directions, parallel and perpendicular with respect to the flow. For both the cases a basic requirement is to get the specimens sufficiently far from the gate and

in proximity of the central symmetry axis of the plaque Doing so avoids border effects, which could determine a material orientation more pronounced than the one observed in the real components.
These criteria have been applied for the measurements appearing in Table 1 cited above.

Product	*Tensile Modulus (normalized)*			*Tensile Max stress (normalized)*		
	Molded T-bar	*T-bar cut from plaque*		*Molded T-bar*	*T-bar cut from plaque*	
		Long	*Transv*		*Long*	*Transv*
40% SGF-PP	1	0.95	0.43	1	0.92	0.41
20% SGF-PP	1	0.94	0.6	1	0.93	0.64

Table. 2: Example of static tensile properties measured on injected T-bars and T-bars cut from plaques for two SGF-PP products. For each property considered, the reported values are normalized with respect to the maximum value measured for each product.

The basic tests used are tensile tests to derive stress-strain curves. This is in agreement with the parameters requested by the material law used, which will be discussed in the following paragraphs..
Now, as anticipated, we go back to the link between the experimental procedure presented here and the method chosen to transfer the data from process simulation, which together form the body of this approach.
It is worth noting that, with this experimental technique, the user associates a measured stress-strain curve to a corresponding flow direction rather than an effective fiber orientation. This matches the choice of a flow variable to express the material orientation as the output from the mold-filling analysis. The material is seen as a “black box,” where the details of fiber orientations are hidden to the experimenter and the designer. Fiber orientations are somewhat embedded in the experimental tests through the way they induce the measured material properties, which is usually referred to as a “phenomenological” approach.
This approach frees the designer from the uncertainties related to the solution of the Folgar-Tucker equation, and can be applied to whichever inclusions might be present within a material, such as talc, rubber, carbon or natural fibers or any combination of these materials.

4.3 Material parameters identification

The input parameters required by MAT_103 are comprised of a uni-axial effective stress vs. effective strain curve in tabular form, or alternatively the material constants which parameterize said curve (variables QR1,CR1,QR2,CR2, as in [10]). Strain rate dependence can be accounted for using the Cowper Symonds model.

4.3.1 Material constants

Automatic identification methods can be used to determine material constants. The stress vs. strain input curve may also be used in tabular form to allow Ls-dyna to fit the data. If more control is sought, concerning the dependence on the strain rate, one could directly introduce the material parameters. This option is also preferred when the simulation needs to be repeatedly run, i.e. during an optimization procedure. The initial phase, when the code fits tabular data, is very expensive computationally if small models are used. Therefore, for material parameters tuning this is a less expensive alternative.

4.3.2 “r”-values

The description of anisotropic material behavior is introduced through the Lankford coefficients, commonly used for expressing a measure of the plastic anisotropy in sheet metal forming, for which MAT_103 was originally developed. These coefficients, often referred to as “r-values”, are defined - and often measured [7] - as a ratio of the true strain in the width direction to the true strain in the thickness direction when a material is pulled in uniaxial tension. As for sheet metal forming, three r-values are requested, labeled as R_{00}, R_{45} and R_{90}; each one is referred to a different pulling direction with respect to the rolling direction. For the present application the rolling direction has been considered as the direction parallel to the flow.

Experimental tests using optical strain measurement [1] were conducted on specimens cut from a plaque at 0° and 90° degrees to the flow lines. This technique is used to measure the local strain on both the X and Y sides of a specimen pulled along a Z direction, using a mirror to inspect both sides simultaneously. (Fig. 4).
The measurements were affected by an excessive noise and data spread when applied to materials having very small elongations at break (less than 5%), while they were sufficiently accurate for materials breaking at strains of about 20% (the SGF-soft PP tested). Due to this drawback, the experimental technique is still under development, and its preliminary results, when acceptable, have been used in this study as a reference only.
Accordingly, a reverse engineering approach has been pursued, aiming to find the set of r values which best reproduce the tensile tests of specimens cut from plaque along the three directions (0°, 45° and 90°).
This has been addressed as a problem of parameter identifications, for which a Multi-Objective optimization through Genetic Algorithms ("MOGA") code has been developed [5].
Following this approach, the optimization procedure aims at identifying a set of parameters (known as Pareto-optimal solutions) that surpass others with respect to all objectives, but are "comparatively accurate" among themselves. Each member of this set is equal to or better than the others members of the set with respect to some, but not all, targets.

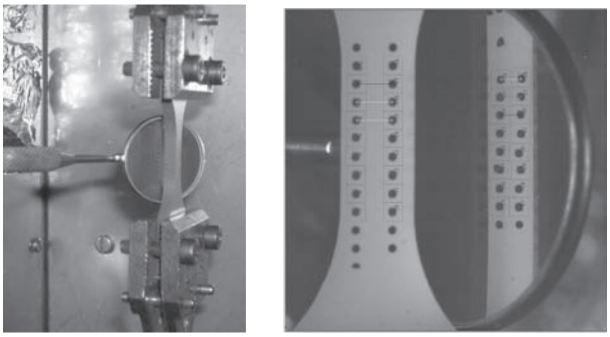


Fig. 4: Experimental measurement of the r-values: a mirror is placed on a side of the specimen in the tensile test, in order to simultaneously measure the strain along its width and thickness using optical methods, based on the tracking of markers.

For this application, the tensile test at the speed of 100 mm/s has been simulated, which determines nominal strain rates of about 4 s^{-1} on the used specimen, In the frame of a multi-objective optimization, the reproduction of the experimental curves force-displacement obtained from tests on two specimens, cut along different orientations, were considered as separate objectives, choosing then, among the Pareto optimal solutions, the set of parameters giving the best global performance on both the tests and, additionally, on the untested orientation, in a validation stage conducted after the optimization.

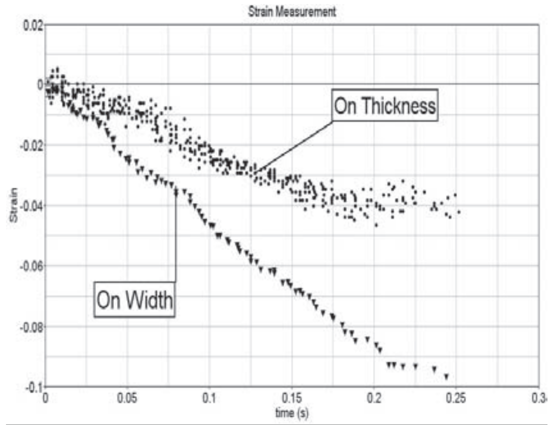
4.3.3 Failure modeling

MAT_103 offers the possibility of modeling the failure through the user subroutine MATUSR_103. In this instance, the dependence of the failure on the strain rate and material orientation, which is typical for SGF-Soft PP, has been imposed through an IF-THEN-ELSE construct to the plastic strain to failure. For the other SGF-PP, a simple criteria based on a maximum strain has been imposed without using the user subroutine.

5 Results

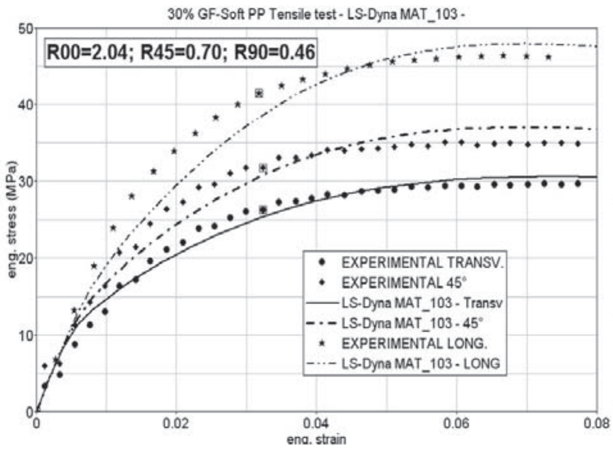
5.1 Parameter identification

The r-values computed with the method described above have been initially compared to the values measured with the experimental technique shown earlier, in a benchmark when a suitable material is used (SGF-Soft PP). Four specimens cut parallel to the flow direction, and two cut perpendicularly to the same have been tested. An example of a strain measurement appears in Fig. 5a; while the average of the measured r-values is on table 3 (fig. 5 (b)). In the same table the r-values from optimization are reported as well. These values have been obtained optimizing the tensile test simulation on specimens cut at 45° and 90°. The best performer on the various specimens can then be chosen from the Pareto set of solutions.



Material: 30%SGF-Soft PP	R00	R45	R90
MOGA Identification	1.8	n.a.	0.35
Experimental	2.1		0.46

Fig. 5a (left): Example of strain measured along the width and thickness on a specimen cut along the flow direction, used to derive the Lankford R_{00} coefficient; Figure 5b (right)/Table 3: r-values measured and from parameter identification, material SGF-Soft PP



Solution from Pareto set	FE Tensile Test average deviation from Experimental data (in %)		
	Specimen orientation		
	90°	0°	45°
Best Average	3.10	4.51	4.91
Best Transv.	3.01	4.45	11.34
Best 45°	20.3	4.56	4.69

Fig. 6a: (left): Tensile test on specimens cut at 0°, 45° and 90° simulated with r-values from parameter identification using the finally selected point in the Pareto set. Material: 30% SGF-Soft PP.
Fig. 6b (right): Table 4: Average deviation from the experimental curve in the simulation of the tensile test for three selected points among the Pareto set.

Table 4 reports the average deviation (in %) from the experimental curves computed in the strain range between 0.02 and 0.08 for three design points selected from the Pareto optimal solutions. Two design points correspond to the solutions that optimize the tests at 90° (labeled "Best Transv°') and 45° ("Best 45°"). The third design point provides a solution equally distant from the tests at 90° and 45° (labeled "Best Average,") where the distance is simply evaluated as the RMS error. Table 4 reports the values of said deviations computed when each of these solutions is applied to the FE reproduction of the tensile test and executed on specimens taken along each orientation. The "Best Average" solution is the top performer of the three tests. The corresponding curves of engineering stress vs. strain are reported in Figure 6b in comparison to the experimental data.
The technique has been then applied to SGF-PP for which no experimental data on the Lankford parameters were available, obtaining the *r-values* reported in Table 5.

Material	*R00*	*R45*	*R90*
30% SGF-PP (A)	2.37	0.60	0.27
30 % SGF-PP (B)	1.99	0.45	0.66
40 % SGF-PP	2.29	0.72	0.49

Table 5- r-values from parameter identification for two 30% SGF-PP and a 40% SGF-PP

5.2 A first box drop test: falling dart

For a first validation, the drop test on a box already presented in a previous study has been used. (see the cited reference for additional details For the present activity, the results are relative to a 20-mm diameter spherical impactor with a mass of 5.148 kg, falling from 0.60 m on a box made of the SGF-Soft PP discussed in the previous paragraph. A curve force vs. displacement on the impactor was recorded.

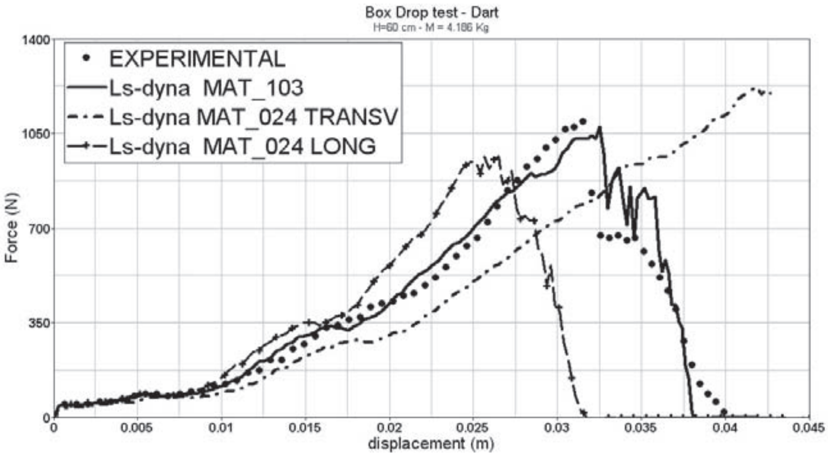


Fig. 7: Box drop test. Curves force displacement obtained with MAT_103 (continuous line), compared to the curves obtained with isotropic modeling and the experimental curve (dots).

The curve obtained from the simulation using the present model is reported in Figure 7; it is compared to the solutions obtained using MAT_024 isotropic modelling in the two cases where the material properties are assigned based on measurements at 0° and 90° with respect to the flow lines. These two cases are referred to as “LONG” and “TRANSV” respectively.
In this case, the improvements achieved by adopting anisotropic modeling are evident. Note that for the input curves available from testing, only an engineering strain measurement was available for high strain rates. Accordingly, the strain at failure could was not known with sufficient accuracy, and the box drop test was used for its calibration. The values obtained were also used for the all the simulations when the same material was used.

5.3 A second box drop test

An alternate impact test was performed on the same box in an attempt to cause a different type and extension of rupture, involving a much wider area of the part. An untested box was used for each experiment. The purpose was to see whether the computational model is capable of correctly predicting the deformation and failure behavior.
The impact position selected was on the side of the box, near one rib. The box is simply supported by the rigid floor, with no constraints. The impactor was a polyamide cylinder having a mass of 4.4 kg and a diameter of 94 mm. Falling heights of 50 cm and 80 cm were tested for both a 30% SGF-PP and a SGF-Soft PP.

A schematic representation of the test is shown in Figure 8. In Figure 9, pictures taken from three exemplars of a box subjected to the test are illustrated. Two (Figures 9a and 9b) are relative to the SGF-Soft PP and were subjected to different impact conditions (falling height of 0.5 m and 0.8 m, respectively). The third picture is about 30 % SGF-PP with a falling height of 0.5 m. The pictures have been processed with an "edge" filter to better show the fracture profiles. In Figures 9c, 9d, and 9e, we show the corresponding virtual boxes after the simulation of the drop test. The fracture is well reproduced. Note that for the fracture to be better predicted, the element failure occurs when one integration point fails, as in [8], setting the MAT_103 variable NINT to 1.

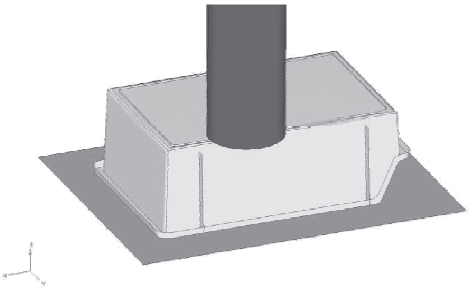
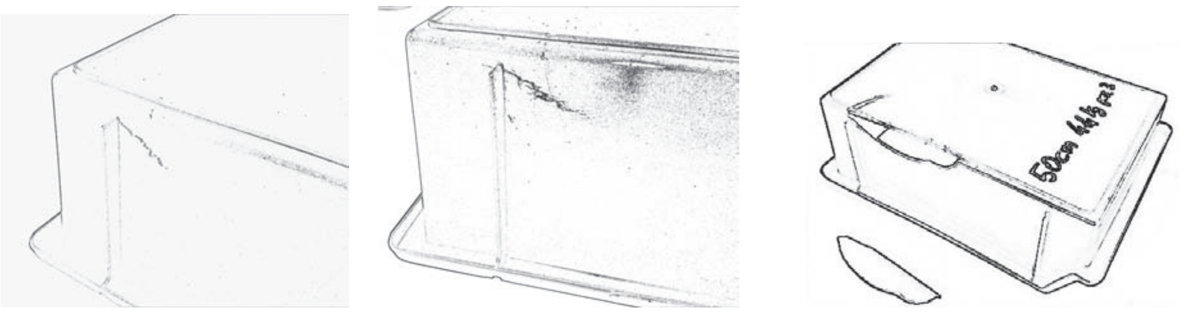


Fig. 8. Schematic representation of the not-instrumented drop test



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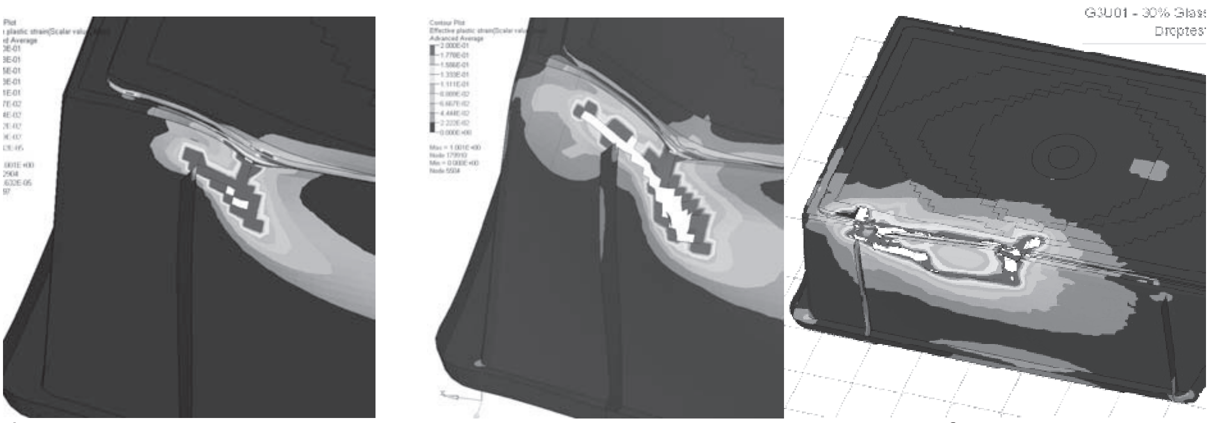

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Fig.9: Box after the impact in the second drop test presented. Above: real test images, below virtual tests. From Left to right: SGF-Soft PP falling height 0.5 m, SGF-Soft PP falling height 0.8 m; 30 % SGF-PP falling height 0.5 m

5.4 A drop test on an industrial component (Faurecia ribbed beam)

Lastly, the method presented here has been used for simulating an impact on a crash-relevant component from the automotive industry, a ribbed beam made of 30% SGF-PP. The impactor was spherical, with a mass of 55 kg and an impact speed of 2.4 m/s. Faurecia Seatings designed and

made the beam, carried out the experimental tests,and made the results available. In Figure 10, the SAE_180-filtered experimental curves acceleration vs. time, relative to four realizations of the same test are shown, together with the MAT_103 results. Apart from the spread of the experimental data, the level of the force is well reproduced by the material model. A slight shift in time is visible. This was already noted in an impact analysis of the same component made from another material [11], and may have occurred due to midplane meshing related approximations.
Furthermore, a good accordance between virtual and real experiment is visible in Figure 11, where the deformation and failure behaviors of the assembly are shown at different points in time.

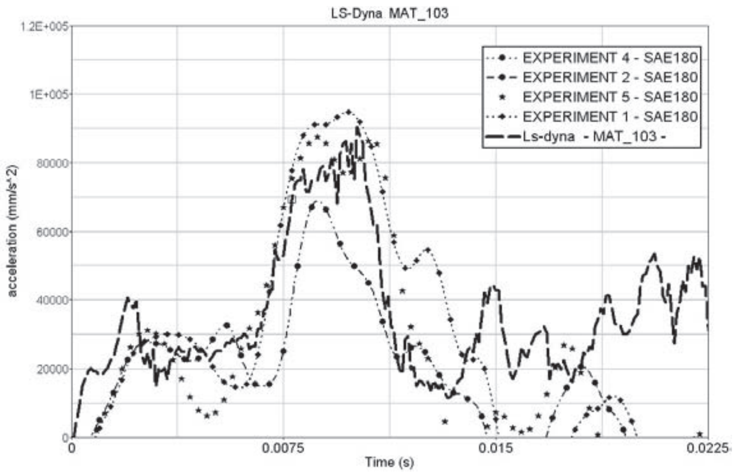

Fig. 10 : Curves of impactor acceleration vs. time: comparison between four experimental realizations and the simulation result for the impact test on the ribbed beam.

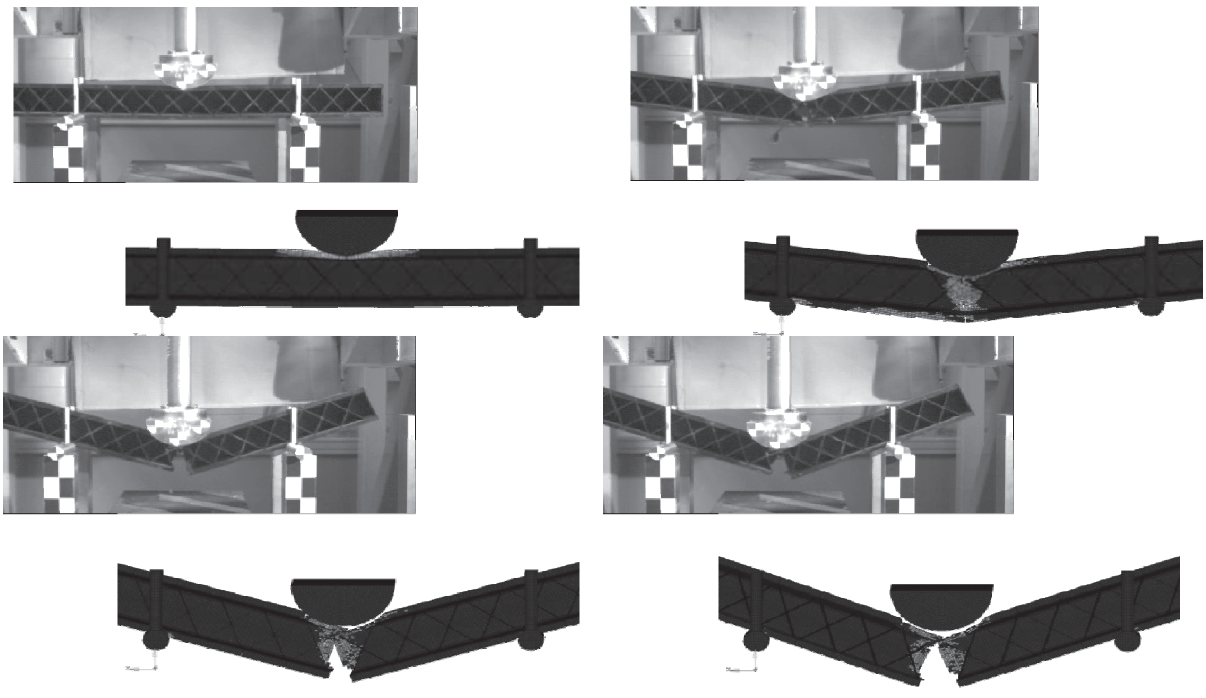

Fig. 11: Real and virtual deformation and failure behaviors of the ribbed beam at different times during the impact sequence. Images from testing courtesy of Faurecia Seatings.

6 Conclusions

This paper presented a simplified approach to the modeling of the anisotropic behaviour which characterizes Glass-fiber reinforced Polypropylene, based on the adaptation and tuning of a material law already existing in Ls-dyna (MAT_103).

A validation on a variety of benchmark cases has been presented, showing that the material orientation induced by the manufacturing process can be simply taken into account in Ls-dyna, obtaining useful and reliable results with a very limited additional computational effort and a standard testing procedure.

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8 Literature

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