1 Introduction

Automotive industry focusses on weight reduction to increase fuel efficiency and reduce CO2 emissions. Achieving both objectives is possible through the creative use of plastics and composites, replacing traditional materials.

Long glass fibre reinforced polypropylene (PP-LGF) is a material often used in semi-structural automotive components, such as front-end module carriers, door modules, dashboard carriers and hatch back doors [1-4]. These parts are generally produced by injection moulding, which gives the engineer freedom to design complex geometrical shapes and ribbed parts, typically needed to achieve light weight structural design (see for instance Fig. 1).

Predictive engineering of mechanical performance and part warpage is often utilized in this design process in order to reduce the development time and costs by limiting the physical prototype parts.

This paper shows some simulation techniques used therein. It will be explained how to utilize both isotropic and anisotropic material properties and analysis techniques. Finally, the need for successful implementation of anisotropic modelling in industrial development projects will be discussed.

2. Isotropic simulation strategy

The use of isotropic simulations is still common practice in automotive industry. Surprisingly, there is no standardized way on how the isotropic material data, like the E-modulus is obtained for reinforced plastics. Depending on how data is measured (datasheet, directly moulded specimen, specimen cut from parts, etc.), different values for stiffness and strength are found due to differences in fibre orientation.

The European Alliance for Thermoplastic Composites (EATC) has devised a method to properly measure isotropic properties from specimen cut from injection moulded plaques [5]. Samples are cut in three directions (0°, 45°, 90°) with respect to flow front direction and classical laminate theory is used to calculate isotropic properties based on a 0°, 45°, 90°, -45° stacking (see Fig. 2).
For parts having a “plate” shape, like door modules, isotropic data will be a good prediction of stiffness and strength. However in structural parts having “beam” shapes, like front-end module carriers usually fibres are more orientated so the isotropic assumption would be too conservative potentially leading to parts which are too heavy (see Fig. 3).

Predicted fibre orientation can be obtained from commercially available injection moulding simulation software like Autodesk Moldflow Insight. Anisotropic simulations then can be performed in a third party FEA software like Abaqus [6]. Linear elastic Moldflow predicted anisotropic stiffness values can be used directly using the Moldflow to Abaqus script. Alternatively a separate micromechanics software program like Digimat-MF [7] can be used to perform non-linear elasto-plastic anisotropic calculations.

In [8], we assessed the accuracy of isotropic, linear anisotropic and non-linear anisotropic simulation methods by simulating a lock stiffness experiment on an existing front-end module carrier made of 30% long-glass fibre filled Polypropylene. The carrier was subjected to a 2 kN load at room temperature and the resultant displacement was measured.

It was observed that the lock stiffness was under predicted by 20% when isotropic values were used. When linear elastic anisotropic material data from Moldflow were directly applied, predicted stiffness was 36% too high, while the results, obtained with a non-linear anisotropic model in Digimat software, were very close to the experiments (-2%) (see Fig. 4). It should be noted however, that, at the time, only linear integrated triangular elements could be used for direct linear elastic predictions. Isotropic and non-linear predictions could be done using quadratic triangular elements. This will influence the results to some extent.

In conclusion, the proper anisotropic simulation gives the correct result, while the isotropic simulation yields a too low stiffness. It means that if a similar new part is to be designed based on simulations with isotropic data, the part may be heavier than needed.

![Fig. 3](image.png)

**Fig. 3.** Mechanical performance of front-end structural part moulded in 40% PP-LGF (SABIC®STAMAX™ 40YM240). Squares = tensile specimen cut at different locations in the part; diamond = datasheet value obtained from directly moulded specimen; circle = EATC isotropic data.

Also it should be noted that the datasheet value is determined on a directly moulded specimen which exhibits high fibre alignment. By consequence, the strength and stiffness of the material are significantly higher compared to application values. Applications designed with datasheet values are likely to encounter failure in real testing.

Note that the few samples having lower properties than the EATC isotropic data are taken from locations with fiber weld-lines. To assess if these locations are critical in a mechanical design, one can compare the direction of the principal stresses with the fiber orientation results from commercially available software like Autodesk®Moldflow Insight.

### 3. Anisotropic simulation methodology

The use of anisotropic material data can yield much more accurate results, enabling a more efficient material use, and hence more weight and cost saving potential. However anisotropic simulations need information on fibre orientation and material quality, both being a result from the injection moulding process used.
4 Anisotropy and warpage prediction

The fibre orientation resulting from the injection moulding process does not only influence local stiffness and strength properties but also the local shrinkage behaviour. In a highly oriented location in a PP-LGF part, shrinkage can be as low as 0.2% in fibre direction while it is 1% in perpendicular direction. This anisotropic shrinkage and the fact that fibre orientation varies within a part will cause part warpage (see for example Fig. 5).

Measures to reduce warpage in industrial applications are the use of sequential gating during filling and packing as well as, in the case of long glass filled materials, to keep the glass fibres as long as possible. Reason for this latter is that short fibres orient easier than longer fibres and thus cause more anisotropic shrinkage which causes warpage. To determine the optimal number and location of the drops on the part numerical simulation is commonly utilised. Accurate prediction of warpage requires good knowledge on fibre orientation.

5 Discussion of anisotropic modelling

5.1 Accurate prediction of fibre orientation

Key in application of anisotropic modelling for both mechanical behaviour as well as warpage prediction is the accurate fibre orientation prediction. Autodesk®Moldflow Insight simulation software is commonly employed to predict the fibre orientation. By default, fibre orientation is calculated as a function of material transport and velocity gradients in the mould using a modified Folger-Tucker law [9]. Recently reduced strain closure (RSC) and anisotropic rotary diffusion (ARD) models are added to deal more correctly with the fibre to fibre interaction observed in long-fibre materials [10].

We found that, with some modifications of the Moldflow software and correct choice of parameters...
acceptable prediction of mechanical properties as function of flow length could be obtained for both shear and expansion flows (see Fig. 6). The fact that the ratio $E_{45}/E_{90}$ is also close to the experimental results, indicates that the thickness averaged fibre orientation, underlying these results, also should be correct.

The advantage of the above mentioned validation strategy is the relative ease of usage. However it only provides information on thickness averaged effective fibre orientation. Although for most structural parts this will lead to accurate predictions of strength and stiffness (see Fig. 4), predicted warpage in bending sensitive parts, like Instrument panels might be incorrect. 

Reason is that fibre orientation over wall thickness varies depending on the local flow conditions. In case of an expansion flow, fibres at the core of a part can be rotated by 90° compared to the fibres at the skin. In case of a shear flow (straight flow front) fibres are all more or less aligned in parallel to flow direction. By consequence, multiple fibre orientation distributions over thickness could lead to the same tensile stiffness.

Thickness dependent fibre orientation is usually quantified by analysis of microscopy cross-section images (see for example [11],[12]). The disadvantage is that sample preparation has to be done very carefully since else measurement results are wrong. An alternative method, successfully applied to short glass filled materials it the use of Computer aided Tomography. This enables visualisation of fibres using non-invasive X-ray scanning (see Fig. 7). This method in principle offers the potential to get a true three-dimensional quantification of fibre orientation tensor in a certain volume (see e.g. [13]). To the authors’ knowledge, the method is not yet successfully employed to derive a fibre orientation tensor distribution in long glass materials. Main reasons are difficulties in fibre recognition, fibre waviness and the limited size of the measurement volume in relation to computing capacity and image resolution needed for post processing.

Fig. 6. Predicted versus measured E-moduli in flow and cross-flow direction, using default parameters in Folger-Tucker and ARD-RSC models (squares) and SABIC optimised parameters (triangles). Measured values shown with circles. Top panel: results of shear flow sample, Bottom panel: Results for expansion flow sample.
5.2 Integration of anisotropy in design process

Design of semi-structural parts usually starts with initial definition of geometry in a CAD environment. At this stage material choice and wall-thickness and/or the use of e.g. metal inserts is still open. In the next phase a material and wall-thickness distribution have to be chosen for this design. (Mechanical) load cases are specified and one checks whether the part will fulfil the (mechanical) requirements using finite element analysis (FEA). This usually happens at a different department or engineering companies. Once the shape and material choice of the part are established, the injection moulding tool is developed, including the choice of number and locations of the gates. Here usually a tool maker is in the lead.

Since currently parts are mechanically designed before injection moulding gate systems are defined, the fibre orientation actually cannot be known in the design stage. A solution has therefore to be found to fit the anisotropic design methods in the current part design scheme. A more integrative approach has to be developed to have successful acceptance of anisotropic simulations of fibre reinforced plastics. This requires an organisational approach different from the one present at many car manufacturers and suppliers.

Another important aspect of enabling anisotropic modelling in engineering practice is the time needed to build and execute the anisotropic simulations compared to the isotropic method currently commonly applied. Current full non-linear elasto-viscoplastic anisotropic modelling approach, using Digimat software with full mean field homogenisation takes approximately 30 times computational time compared to a simple isotropic calculation. Utilizing a simplified solver (hybrid solver [7]), reduces this factor to 7.5 (see Fig. 8). The differences in memory requirement are less extreme.

Fig. 8, Relative effect of anisotropic calculation methods on computational time and memory usage in an explicit impact simulation: a 55 kg impactor hits a cantilevered injection Moulded beam (30% PP-LGF, l x w x h x t= 450 mm x 70 mm x 45 mm x 3mm) at 2.4 m/s. Simulation time equals 15 ms. isotropic calculation, full anisotropic elasto-viscoplastic (EVP) and EVP with faster hybrid solver [7]. Top: Model overview, Bottom: Computational times and memory usage. (Simulations done using single CPU, using ABAQUS 6.11.1 [6], Digimat-MF 4.4.1 [7]).
6. Conclusion

Fibre reinforced plastics offer great potential for weight reduction of semi-structural parts. Although anisotropic simulation methods are in place and give reasonable accurate results, they are still not widely applied in automotive part design. Great efforts are made in correct prediction of fibre orientation. However, the (extra) time needed to build and execute the anisotropic simulations as well as the need for an integrated design approach between CAD design, tooling and mechanical simulations are still a bottleneck.

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References


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