# Improved Quality Prediction of Injection Molded Fiber Reinforced Components by Considering Fiber Orientations

Sascha Pazour, Dr. Wolfang Korte, Dr. Markus Stojek

PART Engineering GmbH

Friedrich-Ebert-Straße, 51429 Bergisch Gladbach

Germany

*For fiber reinforced parts the consideration of anisotropic material behavior is required to receive reliable results. In the scope of this fact a procedure is described how to consider these effects in terms of process-structure interaction and how to achieve possible benefits such as weight reduction and shorter development cycles shown for examples of the industry .*

*The developed procedures show how to consider the anisotropic mechanical behavior of injection molded short-fiber-reinforced plastics parts in FE analysis. It is shown how the existing information, which is provided by injection molding simulation software, can be processed and transferred into mechanical simulation models.  The procedure is outlined with practical applications.*

*Keywords: Composites, Fiber-Reinforced, Injection molding, Process-Structure-Interaction, Anisotropic*

## 1. Introduction

It is evident that due to the anisotropic behavior of short-fiber-reinforced parts the structural analyst is interested in considering these effects. Such a consideration may result in a more accurate prediction of the mechanical behavior of the investigated component or part.

In the following article, a strategy will be described to predict stiffness and strength of injection-molded short-fiber-reinforced plastics. It is based on the theory of the homogenization of a composite, taking into account the special behavior of such a material.

## 2. General

The injection molding process causes a local anisotropic material behavior within the part due to fiber orientations in the short-fiber-reinforced plastic. These orientations vary not only at different locations in the part but also across the wall thickness. The laminar flow of the melt in combination with the velocity profile in the flow channel lead to characteristic fiber orientations across the wall thickness with fibers mainly aligned parallel to the flow direction in the outer so-called shear layers and fibers mainly aligned transverse to the flow direction in the mid layer.

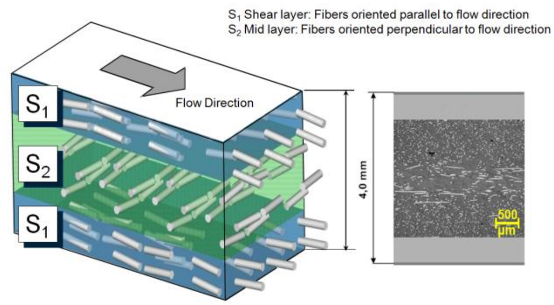


Figure 1. Fiber Layers Across the Wall Thickness of an Injection Molded Part [BASF]

## 2.1 Micromechanics of short-fiber-reinforced plastics

In the past a lot of researches dealt with micromechanical modeling of fiber-reinforced plastics. In this paper we consider the theory of Tandon and Weng. Tandon and Weng developed an analytical transversal isotropic approach. They derived closed analytical equations from Eshelby's theory of ellipsoidal inclusions. Their model can be extended also for the orthotropic case but remains purely elastic. The model provide the elastic response of the composite in different directions by assuming that the composite behaves as a continuum. The individual behavior of the different phases of the material - fiber and matrix - cannot be distinguished anymore.

However for a lot of cases in practical applications these assumptions do not restrict the usability of this model in order to make reasonable statements with regard to the part stiffness and design limit.

## 2.2 Consideration of fiber orientation distributions

In real injection molded short-fiber-reinforced parts there are fiber orientation distributions instead of ideally aligned fibers and because of the fact that in a finite element model the element size is never small enough to include only one fiber the material model has to have properties referring to that distribution. It is evident that for nearly ideal aligned fibers (narrow fiber distribution curve) different mechanical properties result than for nearly un-oriented fibers (broad fiber distribution curve). This has to be considered in the definition of the anisotropic material properties.

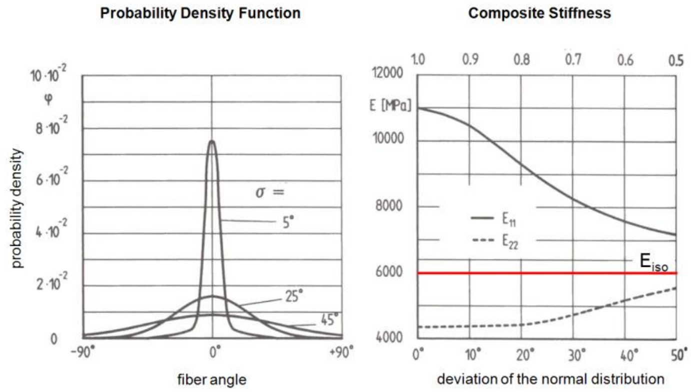


Figure 2. Influence of the Degree of Orientation onto the Composite Stiffness (Mohr-Matuschek)

For this a so-called orientation averaging can be applied (Advani and Tucker). The mechanical properties determined for the idealized unidirectional volume element are weighted with their local degree of orientation. For a narrow distribution the degree of orientation is close to unity and for a very broad distribution close to zero (quasi-isotropic). The information about the local degrees of orientation can be extracted from the orientation tensor which is provided for every element as standard output by most injection molding solvers.

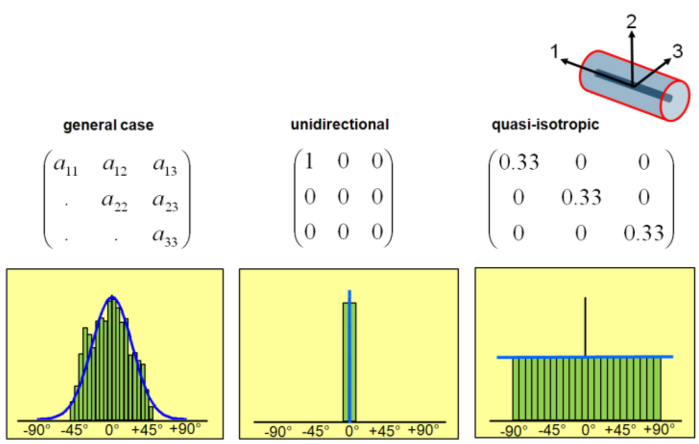


Figure 3. Orientation Tensor

## 3. Fundamentals

The analysis and interpretation of results obtained by means of an anisotropic analysis is generally carried out otherwise than it is done in an isotropic analysis. In particular, the evaluation of all stress and strain invariants such as principal stresses and strains or the von Mises stress is not meaningful in an anisotropic analysis. Because all components of the stress and strain tensor here refer to local element coordinate systems that are generated by the software CONVERSE. Accordingly, only the components of the stress or strain tensor should be evaluated. Since by definition in CONVERSE, the 11-direction is always aligned with the main fiber orientation direction, the individual tensor components e.g. $\sigma_{11,}$ $\sigma_{22,}$ $\sigma_{33}$ therefore also always relate to the fiber orientation directions within each element. For example, for fiber orientations transferred from surface or midplane injection molding models, the stress component $\sigma_{11}$ of the composite is the stress in fiber direction. The stress component $\sigma_{22}$ is the stress component of the composite transverse to the fiber direction in the plane of melt flow. The stress component $\sigma_{33}$ is the stress component of the composite transverse to the fiber direction transverse to the plane of melt flow (i.e. pointing in direction of the wall thickness). In a surface or midplane injection molding simulation fiber orientations in the out-of-flow plane do not exist by definition. The melt flow plane is assumed parallel to the local part surface respectively cavity wall.

In the case of fiber orientations transferred from 3D injection molding models, the stress components $\sigma_{22}$ and $\sigma_{33}$ cannot further distinguished with regard to their alignment to the cavity wall. Here, the fibers can be oriented in all spatial directions (melt flow respectively fiber orientation in wall thickness direction is possible).

### 3.1 Strength Assessment

If a strength assessment has to be done based on an anisotropic analysis the calculated stresses respectively strains have to be compared with appropriate failure indicators. The assessment of failure has to be done by distinguishing the local fiber orientations. Accordingly, different failure indicators parallel and transverse to the fiber orientation have to be determined. As an estimate for the strength of the composite parallel to the fiber direction ($\sigma_{11}$) the strength of the composite ($\sigma_B$ or $\sigma_S$) from material Databases such as CAMPUS Plastics may be used. As an estimate for the strength of the composite transverse to the fiber direction ($\sigma_{22}$) the strength of the matrix material of a corresponding unreinforced grade may be used. These values are of course only rough estimates. More reliable failure limits can be obtained by using injection molded test plaques with a film gate in order to achieve aligned fibers along the side of the plaque. From these plaques specimen can be taken for tensile tests parallel and transverse to the fiber orientation.

In the strength assessment it has to be taken into account that CONVERSE uses an anisotropic but still linear-elastic material model. That is, if the material exceeds significantly the range of a nearly linear stress-strain characteristic, with the linear-elastic material model used in CONVERSE an ultimate material failure can´t be predicted directly. The calculated stresses and strains would more or less deviate from the real nonlinear stress-strain characteristic. The limitation of the linear-elastic material model that is applied in CONVERSE is for most practical cases acceptable. Since, fiber-reinforced plastics behave as opposed to unreinforced grades over a relatively large range approximately linear. Furthermore plastics parts undergoing long term loads or dynamic loads should anyway not stressed to the nonlinear range. Stresses should be kept well below the fracture or yield point and should remain in the nearly linear-elastic range. Hence, the tabulated ultimate failure values of the material, in the context of a conservative part design, have to be reduced accordingly and can then be compared with the calculated linear stresses and strains.

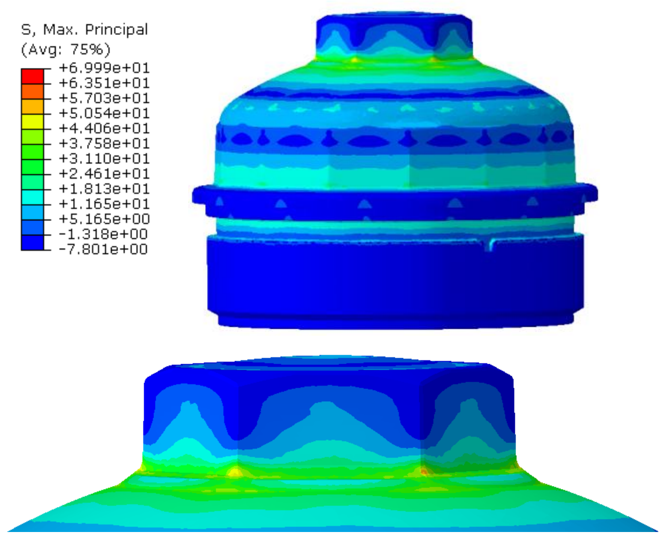


Figure 4. Isotropic Model without CONVERSE

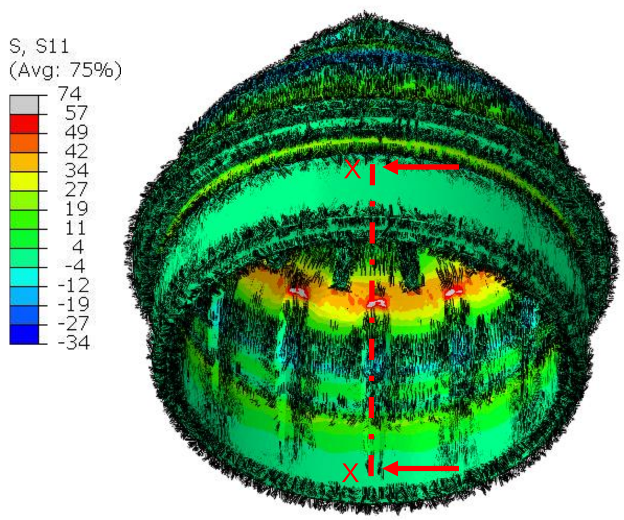


Figure 5. Anisotropic Model with CONVERSE (Fibers in 11-Direction),
Stress in 11-Direction

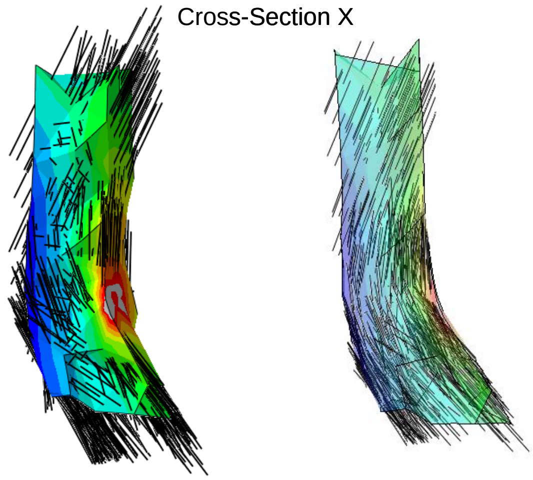


Figure 6. Section X: Anisotropic Model with CONVERSE (Fibers in 11-Direction), Stress in 11-Direction

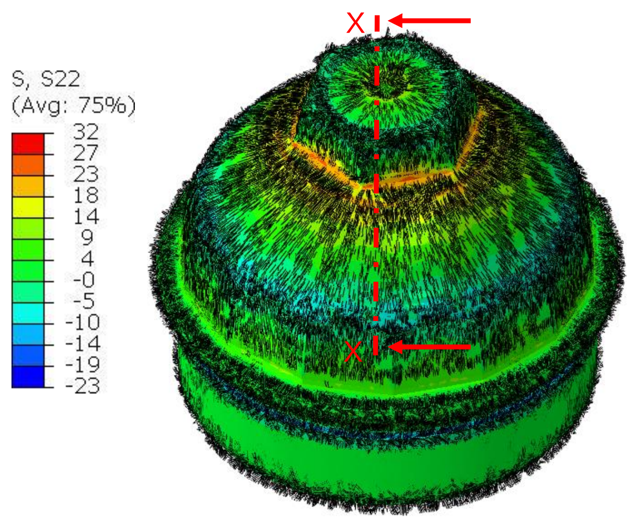


Figure 7. Anisotropic Model with CONVERSE (Fibers in 11-Direction), Stress in 22-Direction

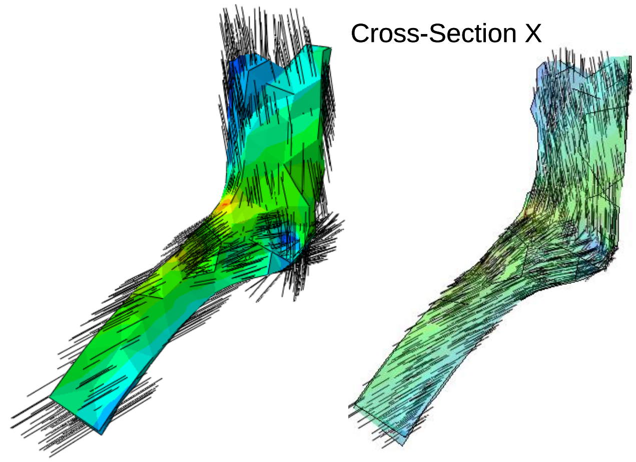


Figure 8. Section X: Anisotropic Model with CONVERSE (Fibers in 11-Direction), Stress in 22-Direction

### 3.2 Stiffness Assessment

The stiffness of a part calculated with the linear-elastic anisotropic material model applied in CONVERSE has to be considered as base stiffness. At which base stiffness is being understood as the stiffness of the part in the approximately linear-elastic range. If the load on the part is such that the stress in the supporting cross-sections of the structure does not exceed the nearly linear-elastic range the calculated base stiffness should reflect the real stiffness of the part within the general model accuracy. This should be valid even if local stress concentrations (e.g. in notched areas) exceed the linear elastic limit significantly and would undergo plastic deformations in reality as far as this yielding does not affect the global deformation of the part.

Also for dynamic oscillating loads and in modal analyses the calculated base stiffness should match the real behavior within the overall model accuracy. On the one hand all mechanical solvers linearize at the operating point the response of the structure anyway for dynamic analyses in the frequency domain. And on the other hand the oscillation amplitudes are comparatively small, so that the assumption of a linear material response is justified anyway as far as the structure is not subjected to an initial load, so that the operating point is shifted into the nonlinear range of the stress-strain characteristic.

## 4. General Procedure

In order to consider the fiber orientations onto the mechanical and thermal material properties in CONVERSE micro-mechanical models are applied. For the determination of the transversal isotropic stiffness of the composite, the approach of Tandon and Weng is implemented. They developed a comprehensive micro-mechanical model based on the investigations of Mori and Tanaka and Eshelby for the computation of elastic properties of short-fiber-reinforced composites.

The transversal isotropic coefficients of thermal expansion are calculated according to the work of Marom and Weinberg.

Since the approaches described above assume unidirectional behavior and do not take into account a fiber orientation distribution, as it is present in real injection molded parts, an orientation weighted averaging of the transversal isotropic properties according to the method of Advani and Tucker is conducted. The whole procedure that is applied in CONVERSE is outlined in the following picture.

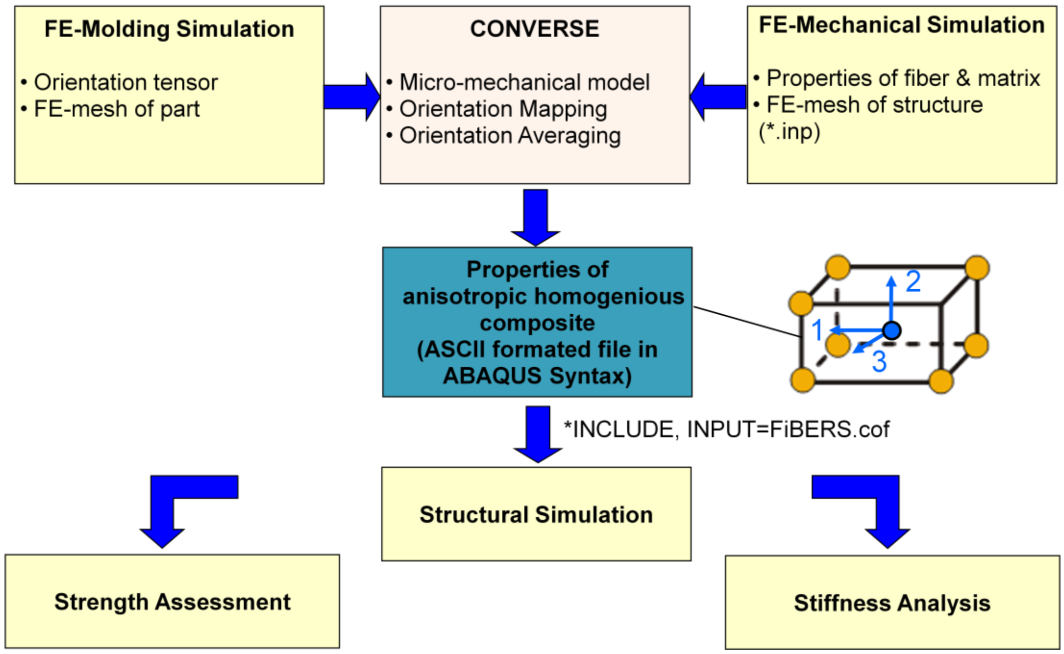


Figure 9. Workflow implemented in CONVERSE

## 5. Elasto-Plastic Behavior of Short-Fiber-Reinforced Plastics

Even though in most cases linear elastic material behavior is enough for several analysis tasks in some cases a elasto-plastic formulation is required. Unfortunately this material behavior can´t be given by built in material models in structural simulation software. Therefore a material formulation in a user subroutine (UMAT) has to be done.

The Mori-/Tanaka-approach delivers the averaged mechanical behavior of the composite as well as the averaged mechanical behavior of the individual phases (fiber and matrix), which is also accessible in the post-processing (stresses/strains in fiber and matrix). The numerical implementation into commercial FE-codes have to done by a user subroutine (CONVERSE/Advanced). Due to the nested equilibrium iterations (in order to determine the elasto-plastic stiffness matrix) to be conducted for each orientation class, CPU times are significantly higher than for built-in material models. The model is basically also feasible to describe time-dependent (visco-elastic, visco-plastic) behavior but is not able to work in the frequency domain.

By the Mori-Tanaka homogenization an effective stiffness is calculated for each microcomposite.

$$\boldsymbol{s} = \left[v_1 \boldsymbol{s}_1 : \boldsymbol{E} + (1 - v_1)\boldsymbol{s}_0\right] : \left[v_1 \boldsymbol{E} + (1 - v_1)\boldsymbol{I}\right]^{-1}$$

Here the composite stiffness of a microcomposite strain concentration tensor has to be taken into account. 0 indicates the matrix and 1 the fiber. In a second homogenization, the effective stiffnesses of the microcomposite are weighted according to their probability of occurrence summed to the overall stiffness of the composite macro.

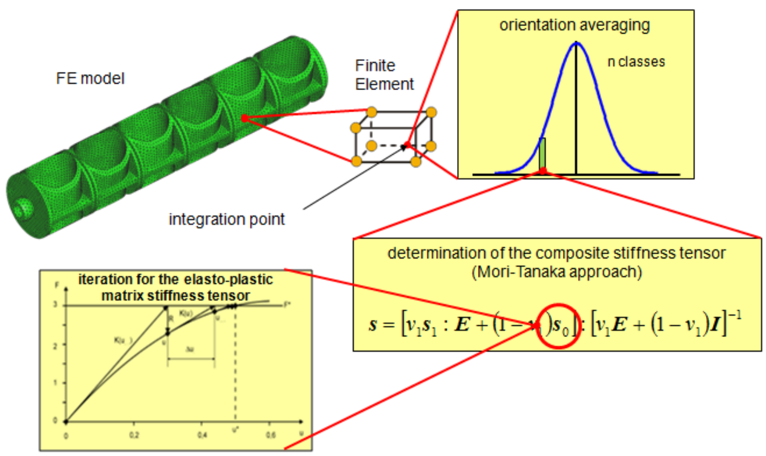


Figure 10. Numerical Implementation of the Anisotropic Elasto-plastic Material Model

## 6. Abaqus Syntax commands

Orientation information has to be given by local orientation systems at each element by using a `*DISTRIBUTION` card and assigned through an orientation card `*ORIENTATION, DEFINITION=COORDINATES`

The fiber distribution is given by orientation tensor values as field variables, where there are only the values in and across the main fiber direction required because of the fact that the sum of all three is always 1 `*INITIAL CONDITIONS, TYPE=FIELD, VARIABLE=1`.

The material properties have to be provided different in the linear-elastic case and the elasto-plastic case. In the linear elastic case the material properties are defined by using the `*ELASTIC,TYPE=ENGINEERING CONSTANTS,DEPENDENCIES=number` command.

Because of the fact, that elasto-plastic anisotropic material behavior is only possible through user subroutine the properties have to be given as a `*USER MATERIAL`.

All these formulations are supported by the Software CONVERSE.

## 7. References


1. Abaqus Analysis User’s Manual, Version 6.12-2, Dassault Systémes Simulia Corp., Providence, RI.
2. CAMPUS website, www.campusplastics.com
3. PART Engineering GmbH website, www.part-engineering.de
4. M. Stommel, M. Stojek, W. Korte, „FEM zur Berechnung von Kunststoff- und Elastomerbauteilen“, Carl Hanser Verlag, 2011
5. Prof. Dr.-Ing. Markus Stommel, Dipl.-Ing. J.-M. Kaiser, ”Homogenisierungsmethoden in der Versagensmodellierung kurzfaserverstärkter Kunststoffe” Saarland University, LPW
6. Tandon, G.P. and Weng, G.J, "The Effect of Aspect Ratio of Inclusions on the Elastic Properties of Unidirectionally Aligned Composites", Polymer Composites, Vol. 5, Nr. 4, John Wiley & Sons, 1984
7. Eshelby, J.D. "The Determination of the Elastic Field of an Ellipsoidal Inclusion and Related Problems", Proceedings of the Royal Society of London 241, No. 1226, 376-396, Birmingham, 1957
8. Advani, S.G. and Tucker, C.L. "The use of tensors to describe and predict fiber orientation in short fiber composites", J. of Rheology Vol. 31 (1987) No. 8, p. 751-784
9. Mohr-Matuschek, U. "Auslegung von Kunststoff- und Elastomerformteilen mittels Finite-Elemente-Simulation" VDI-Fortschrittsberichte, Reihe 20 Nr. 68, VDI-Verlag, Düsseldorf, 1992