

Strength Assessment of Injection Molded Short-Fiber-Reinforced Plastic Components

Wolfgang Korte, Marcus Stojek, Sascha Pazour

PART Engineering GmbH, Germany

Abstract: Components made of short-fiber-reinforced plastics (SFRP) are stressed highly both mechanically and thermally. Therefore an intelligent component design is required in order to fully exploit the potential of these materials. Hence, the design of such components must be based on a reliable strength assessment. For this purpose models for the description of the anisotropic and elasto-plastic failure behavior of SFRP are required. In contrast to the widespread use of SFRP, methods for a reliable strength assessment based on FE analyses for components made of these materials have not been sufficiently developed yet. This paper presents an approach for the strength assessment of SFRP components based on FE analyses. In the scope of this appropriate failure limits and failure criteria for these materials are presented.

Keywords: Anisotropy, Failure Criterion, Injection Molding, Polymer, Plastics, Short-Fiber-Reinforced Composites, Tsai-Hill, elasto-plastic

1. Introduction

The use of injection molded SFRP parts take place in many different industries. In particular, in the automotive industry SFRP are increasingly being used as the preferred engineering plastic. This is due to the excellent mechanical and thermal properties of these materials compared to non-reinforced grades. The use of these materials enable the manufacturer of automotive components to a significant weight reduction compared to metallic materials and lower manufacturing costs as well due to the fact that a plastic part is typically a finished part without any further processing necessary.

The molding process is the cause for the formation of a specific microstructure within the molded part, which in turn is the root cause for the mechanical properties of the part. Especially for plastics this microstructure can be molecular orientations or in the case of SFRP fiber orientations, leading to an anisotropic material behavior. In this sense it can be said that the material is composed during the molding process. In figure 2 the effect of fiber orientation onto the mechanical behavior of a plastic is shown.

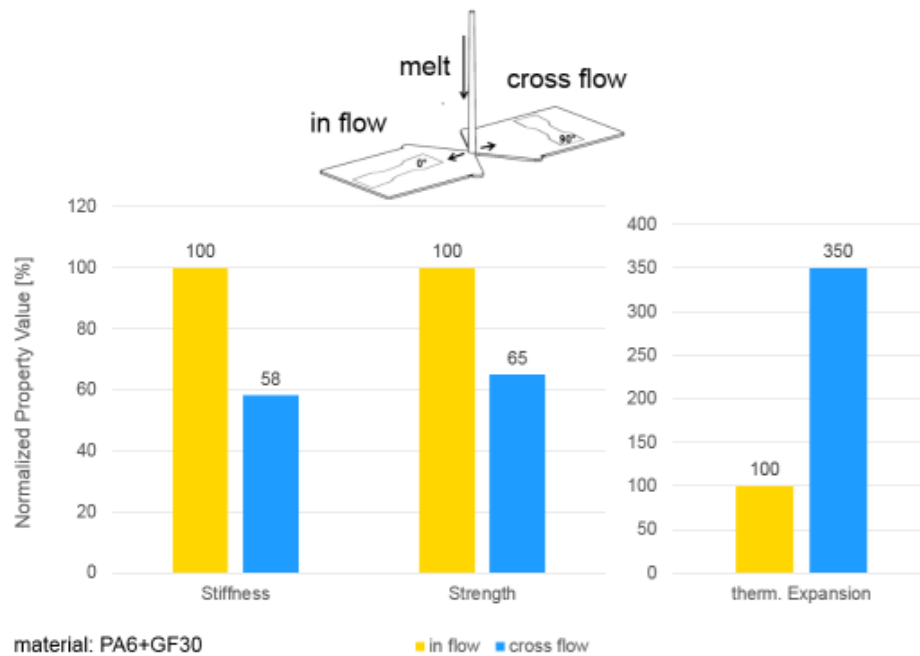


Figure 1: Influence of Fiber Orientation on Material Properties

It is evident that due to the described strong impact of the injection molding process on the properties of the manufactured part itself the structural analyst is interested in considering the effect of anisotropy on part stiffness and strength. Such a consideration may result in a more accurate prediction of the mechanical behavior of the investigated component.

Whereas the proper description of the stress-strain behavior of the part is a question of a suitable material model that in the case of SFRP is e.g. capable to consider anisotropic elasto-plastic behavior the proper assessment of the part failure is a question of a suitable failure limit and failure criterion. In this paper is the focus on the failure assessment, assuming that a suitable material model was already chosen in order to calculate the local stresses and strain in the part properly.

2. Local Component Properties

In technical parts there is not a uniform component strength rather than a local strength distribution depending on manufacturing and design. Particularly for injection molded SFRP parts the material is generated during the molding, depending on the position in the part the material possess different properties dependent on the local fiber orientation. Additional factors that

influence the local component strength are the degree of multiaxiality and to which amount the local stress on the component surface propagates into the cross section. In the following the influence of these different factors will be described.

Influence of fiber orientation

As already outlined SFRP have significant different mechanical properties parallel and transverse to the fiber direction. Opposed to unidirectional endless fiber reinforced composites where the part is composed of several unidirectional layers for injection molded SFRP parts there exist a fiber orientation distribution instead of ideally aligned fibers.

The orientation state of these fibers at every discrete location in the part can be described more in a probabilistic rather than in a deterministic manner. It is evident that for nearly ideal aligned fibers (narrow fiber distribution curve) different mechanical properties result than for nearly randomly oriented fibers (broad fiber distribution curve). This has to be considered in the assessment of the local strength of the part (Figure 2).

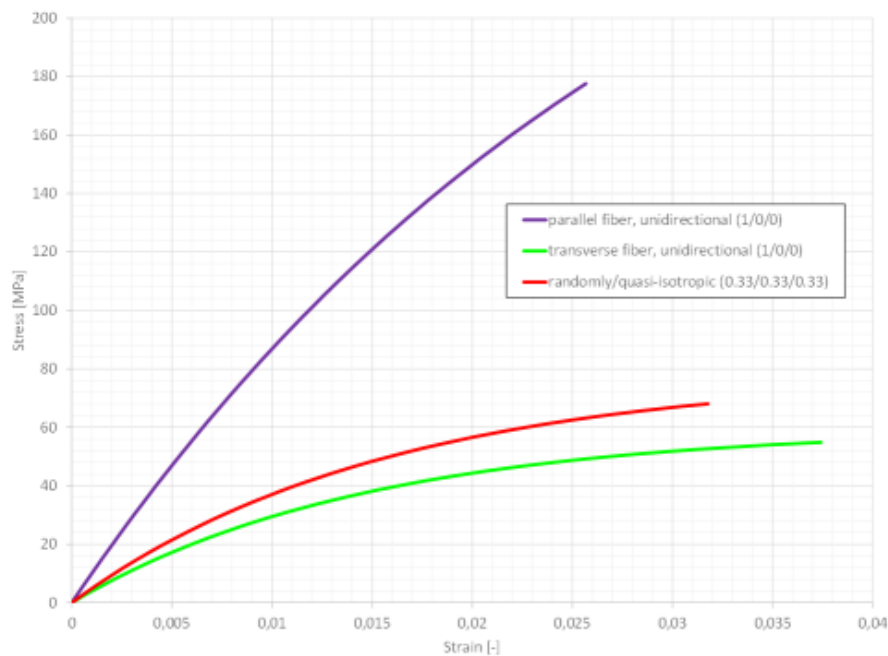


Figure 2: Stress-/Strain-Curves for Different Fiber Orientation States (PBT+GF20)

For a narrow distribution the degree of orientation is close to unity (nearly uniaxial) and for a very broad distribution close to zero (nearly randomly respectively quasi-isotropic). The information about the local degree of orientation and the principal orientation direction can be extracted from

the orientation tensor which is provided for every element as standard output by most injection molding solvers.

Influence of triaxiality

In real parts most probable multiaxial stresses occur in contrast to specimen e.g. for the determination of the materials' mechanical properties. Hence there is a need to choose a failure criterion that is capable on the one hand to take into account multiaxial stresses and on the other hand considers the anisotropy of the material strength with regard to the local fiber orientation.

Another effect to be taken into account is the increasing brittleness of the material due to triaxiality which in turns leads to decreasing allowable strains and a change in the fracture mode from e.g. ductile fracture due to deviatoric stresses to brittle failure due to normal stresses. This effect is obvious in notches where a brittle failure occurs frequently though the material itself behaves ductile under unidirectional loading. This effect can be explained mechanically with the increasing constraint of shear deformations, that are typical for a ductile fracture, if a multiaxial stress state is present. This leads to the need to evaluate the specific allowable material strength or strain respectively with regard to the local degree of triaxiality in the part.

Influence of stress propagation into local cross section

If the stress hot spot comprises only small areas of the cross section e.g. typical for sharp notches these stresses do not have to be evaluated as critical for the part failure as stresses that exist uniformly across the local wall thickness of the part. Therefore there is a need to evaluate what can be considered as failure with regard to the part not to be mixed up with failure due to the ultimate exceeding of the material strength.

3. Proposed Approach for Strength Assessment

In Figure 3 an approach is outlined that we propose in order to make a strength assessment of injection molded SFRP parts.

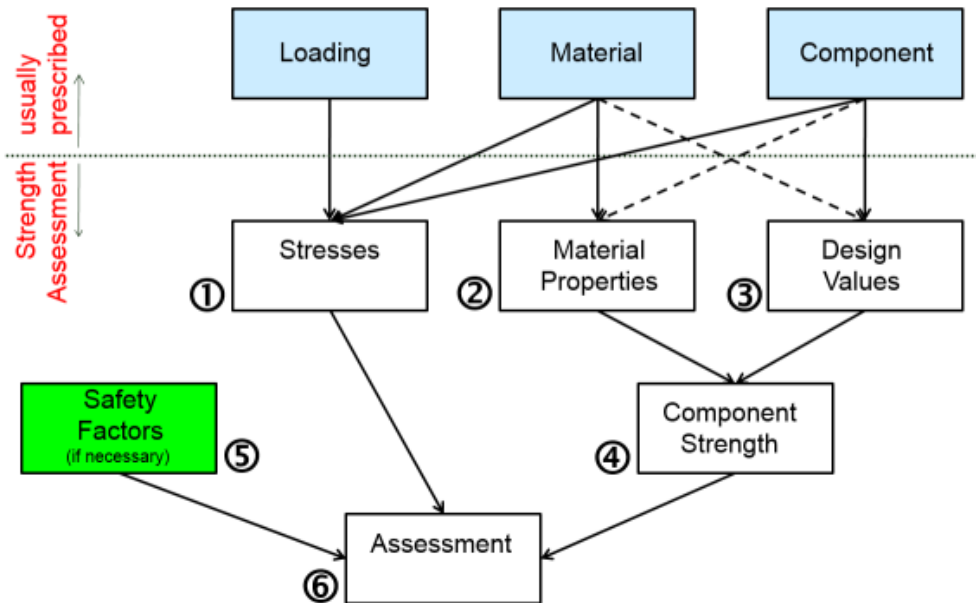


Figure 3: Proposed Approach for Strength Assessment of SFRP Parts

Basis of the assessment are the loading, the material chosen and the component design. In order to determine the stresses and strains in the component properly, in this paper it is assumed that a suitable material model for SFRP was used for the FE analysis, e.g. an anisotropic elasto-plastic model. Which implies that a suitable software e.g. Converse (Converse, 2015) was used in order to provide the local fiber orientation in the part element-wise as well as the material properties needed for such an anisotropic elasto-plastic material model.

Second the strength properties of the material are needed in form of appropriate allowable stress or strain limits. As mentioned earlier in the case of injection molded SFRP parts the material does not exist by itself it is generated during manufacturing. However accessible are just material properties that are determined with e.g. ISO tensile specimen either molded directly or cutted from test plaques to which it is referred in the following as tabulated values. These tabulated values do not necessarily reflect the values that exist in the component. The manufacturing conditions in the specimen are in general different than the conditions in the component this is particularly true for the local fiber orientation. Hence an approach is needed that is capable to determine the strength properties of the material for different degrees of orientation based on the tabulated values.

Third design values are defined that consider the effects of the local degree of orientation, the local degree of triaxiality and the propagation of stress from the component surface into the local cross section. The design variables together with the orientation dependent material strength determine the local component strength at each position in the part.

Eventually the ratio of the computed local stress and local component strength provides the utilization ratio which is the inverse of the safety factor. Utilization ratios larger than unity indicate a component failure.

4. Orientation-Dependent Material Failure Limits

In order to determine a functional dependency of the material failure limit on the degree of orientation which is a characteristic number for a particular orientation distribution it is obvious that for sufficient discrete points the related stress respectively strain limits are required. Each orientation distribution is mathematically represented by the orientation tensor which in turn can be obtained as output from an injection molding simulation.

The eigenvalues of the orientation tensor - the so-called a -values - which can be computed by a principal axis transformation are a representation of the particular shape of the fiber orientation distribution. For instance $a_1 = 1$; $a_2 = 0$; $a_3 = 0$ represents a unidirectional distribution and $a_1 = 0.33$; $a_2 = 0.33$; $a_3 = 0.33$ represents a quasi-isotropic (random) distribution without any predominant fiber direction. The principal axis system gives the directions in which the fibers are aligned with the 1-direction always the direction in which most of the fibers are aligned and the 2- and 3-direction always perpendicular to that direction. Assuming transversely isotropic behavior for SFRP which is a plausible assumption the mechanical properties in 2- and 3-direction are equal for unidirectional conditions where $a_1 = 1$, hence all fibers are aligned in the same direction. For such conditions the strength limits in fiber and transverse to the fiber direction could be determined directly if ideally unidirectional oriented specimen could be manufactured. Unfortunately this is practically not possible. There are always deviation to an ideal orientation at each position of the specimen and also there are different orientation across the wall thickness of the molded part due to specific flow effects (Figure 4). Even if the specimen are cutted from plaques that are molded with a film gate there is not a 100% orientation of the fibers.

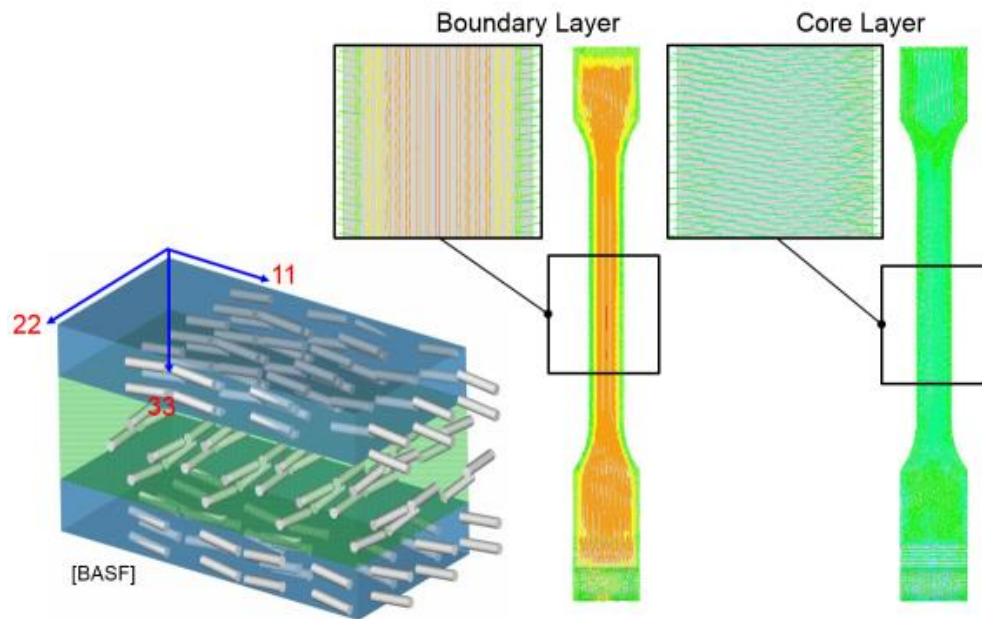


Figure 4: Fiber Orientation in Tensile Specimen

The proposed procedure in order to attain the orientation-dependent strength limits of the material is to conduct short term tensile tests with specimen cutted out of test plaques with an angle of 0° , 30° and 90° to the flow direction. In a re-engineering approach with an anisotropic elasto-plastic material model (Hill yield criterion) the specimen are simulated with consideration of the fiber orientation that are provided from an injection molding simulation. This approach then delivers the Hill yield ratios R_i as a function of the eigenvalues of the orientation tensor a_i . With that also the strength respectively strain limits of the material are defined, by scaling of the complete stress-/strain-curve with the yield ratios for different fiber orientation.

5. Component Strength

In order to determine the local component strength the design values are needed. The effect of local fiber orientation is considered element-wise with the a -values of the orientation tensor and the principal orientation direction. In Abaqus this is realized with local element orientations for the principal orientation direction with the 1-direction always aligned in fiber axis and with field variables for the eigenvalues a_i of the orientation tensor. In this manner for each element a belonging orientation-dependent stress-/strain-curve can be assigned.

The influence of the triaxiality on the material strength respectively strain is considered with the stress triaxiality number $\eta = -p/q$, p is the hydrostatic pressure and q is the Mises equivalent stress. The triaxiality number can be requested in Abaqus as output variable TRIAX. With this number

the allowed strain limit of the material is scaled from its maximum value breaking strain for unidirectional loading to a minimum allowed strain at the transition point between linear-viscoelastic and nonlinear viscoelastic behavior for high triaxiality.

The influence of the triaxiality on the failure value itself is considered with a suitable failure criterion for which the Tsai-Hill criterion was chosen. Since in its original formulation the Tsai-Hill criterion is only valid for unidirectional behavior here it is defined as a function of the eigenvalues of the orientation tensor a_i , which are accessible for each element as field variables (Korte, Stojek, 2015).

In fact by applying this procedure for each element a different value of the Tsai-Hill value follows. The square root of the Tsai-Hill value can be interpreted as utilization ratio since the allowed limit stresses are in the denominator and the actual stresses are in the nominator. For values of the Tsai-Hill criterion larger than unity failure has to be assumed. As allowed limit stresses the ultimate breaking stresses in the different directions were used.

6. Application Example

As an application example in Figure 5 a bicycle brake lever is shown. The lever is made out of a PBT with 20 percent glass fiber content. In order to test the components stiffness and strength the test set-up also shown in Figure 5 was used (Stommel, 2015).

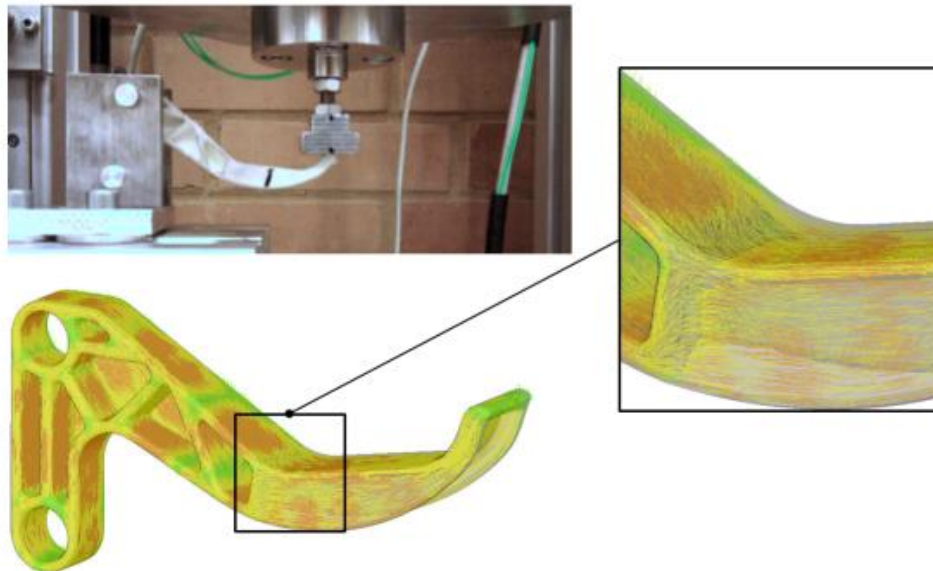


Figure 5: Test Set-up and Fiber Orientation in Bicycle Brake Lever

The component was simulated with Abaqus with an anisotropic elasto-plastic material model with consideration of the fiber orientation distribution. The fiber orientation were obtained from an injection molding simulation and then were transferred in the mechanical FE model by applying Converse that provided the appropriate material parameters for the anisotropic elasto-plastic material card in Abaqus as well (Pazour, 2015). The assessment of the component strength was conducted in post processing with a software prototype (S-Life/Plastics, 2015) that is capable to read an Abaqus odb file. As already described in this manner it is possible to access element-wise the a-values of the orientation tensor that are stored in the odb file as field variables. Subsequently within the software for each element the orientation-dependent value of the utilization ratio (square root of the Tsai-Hill value) was computed. A contour plot of the computed utilization ratios is shown in Figure 6.

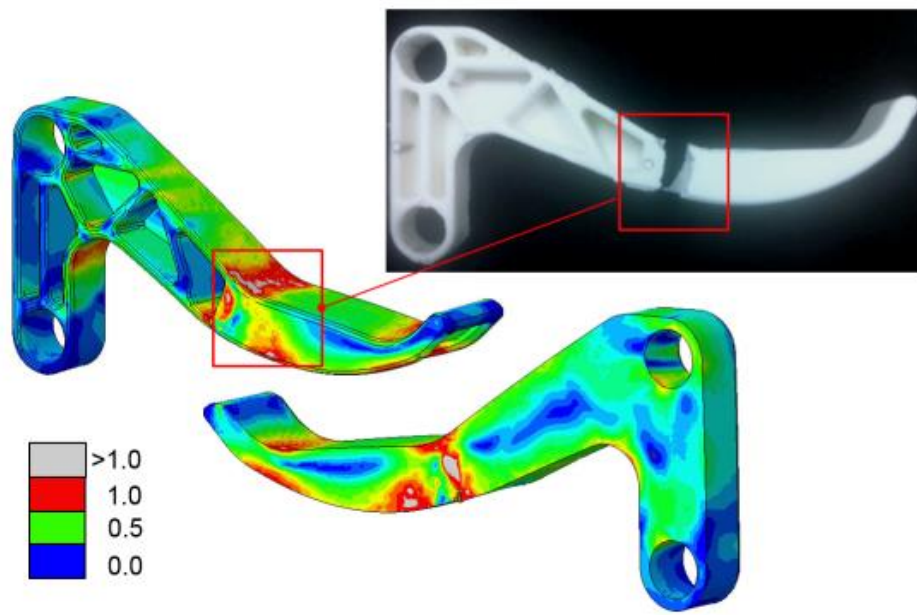


Figure 6: Utilization Ratio and Failed Part

For values larger than unity failure has to be assumed. The computed utilization ratio indicates a good correlation to the failed tested part with regard to the failure location, also shown in Figure 6. As well a good correlation with the failure displacement respectively force was predicted with the applied utilization ratio as failure indicator.

7. Summary

In the scope of this paper an approach was presented that is capable to give good failure predictions for injection molded SFRP under mechanical loading. In the computed utilization

ratios as failure criterion an orientation-dependent formulation of the Tsai-Hill equation was used. Not yet implemented in the computation of the utilization ratio is the proposed consideration of the influence of the triaxiality on the failure limits as well as the effect of stress propagation from the component surface into the component.

8. References

1. Korte, W., Stojek, M., “Entwicklung einer Software zur orientierungsgradabhängigen Kalibrierung eines anisotrop elasto-plastischen Standard-Materialmodells zur FEM-Simulation von kurzfaserverstärkten Kunststoffbauteilen” unpublished report ZIM Koop research and development project No. KF3056701RR2, Bergisch Gladbach, Germany, 2015.
2. Korte, W., Stojek, M., “Entwicklung eines Verfahrens zur Festigkeitsbewertung von kurzfaserverstärkten Kunststoffbauteilen” unpublished report ZIM Solo research and development project No. EP110100, Bergisch Gladbach, Germany, 2013.
3. Stommel, M., “Entwicklung und Umsetzung einer hybriden Simulationsmethodik zur effizienten Berechnung und Auslegung von kurzfaserverstärkten Kunststoffbauteilen” unpublished report ZIM Koop research and development project No. KF2214510RR2, Saarbrücken, Germany, 2015.
4. Pazour, S., “An Easy Procedure for Anisotropic Non-Linear Behavior of Short-Fiber-Reinforced Plastics” Proceedings Simulia Community Conference 2015, Berlin, Germany
5. Converse, Software, PART Engineering GmbH, Bergisch Gladbach, Germany, 2015
6. S-Life/Plastics, unreleased software, PART Engineering GmbH, Bergisch Gladbach, Germany, 2015

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