FATIGUE LIFE PREDICTION OF SHORT FIBER REINFORCED PLASTIC COMPONENTS

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Introduction

In automotive engineering the development of light weighted structures is very important to save fuel and so to reduce the pollution. Therefore the usage of new materials like fiber reinforced plastics is very attractive even for dynamically loaded parts. Nevertheless, there is still little knowledge about the fatigue behavior of fiber reinforced plastics. So it is difficult to make an optimum design according to the divergent requirements on weight and strength. Some research works have been already done by BMW [1, 2] and others [3-5].

Four years ago a research project was started joined by BMW, University of Leoben, Engineering Center Steyr and EMS-Grivory to investigate the fatigue behavior of glass fiber reinforced plastic materials and to develop and establish methods for fatigue life prediction of dynamically loaded plastic components [6]. A lot of static and fatigue tests on specimens and also on real automotive components have been performed. Methods, which use injection molding simulation results, have been implemented into the commercial fatigue life prediction software FEMFAT. The main focus of this project was, to establish a simulation process consisting of injection molding simulation, stress analysis with the finite element method and fatigue life prediction, which is practicable in daily engineering work.

Influence Parameters on Fatigue Life

For metallic materials as steel, cast iron, aluminum and magnesium it is well known, that the fatigue life until crack initiation is influenced by a lot of different parameters:

- Material ductility
- Size
- Surface treatments as shot peen, roll, inductive hardening, etc.
- Surface roughness
- Process influences (forming, casting)
- Temperature
- Type of loading (tension, compression, bending, torsion)
- Mean stresses, residual stresses
- Variable loads
- Multi-axial loading
- Plastic deformation
- Sequence effects

The quality of fatigue life prediction strongly depends on the knowledge and quantification of these parameters, but it depends also on the quality of material parameters, on the quality of the finite element mesh and stress results, and on the suitability of the applied fatigue life prediction methods. Nevertheless, fatigue life is always a statistical quantity valid for a specific survival probability, which only makes sense together with a range of dispersion (assuming e.g. a Gaussian probability distribution of test results for a given stress amplitude).

For fiber reinforced plastic materials the situation is even more complicated. The failure mechanisms are completely different. Fig. 1 shows the fracture surface of a tested specimen, where it can be seen, how the matrix detaches from the fibers.

Fig. 1: SEM micrograph of the fracture surface of a short specimen of PA 6T/6I-GF40MX2

Additional influence parameters on fatigue life for fiber reinforced plastics are:

- Fiber orientation, material anisotropy
- Type of material (fiber-matrix-system)
- Frequency dependency
- Moisture absorption
- Environmental media (oil, brake fluid)
- Joint lines
- Aging
- Creeping
- Fabrication
- Complex Failure criteria due to different damage mechanisms

In the first part of this research project the main focus was the investigation of the inhomogeneous material anisotropy resulting from the fiber distribution and orientation, which can be fully characterized by a symmetric 3x3 tensor of second order. This orientation tensor contains two kinds of information:

- The three eigenvectors define the principal directions of anisotropy.
- The three eigenvalues define the shares of fibers in the three principal directions of anisotropy, see Fig. 2.

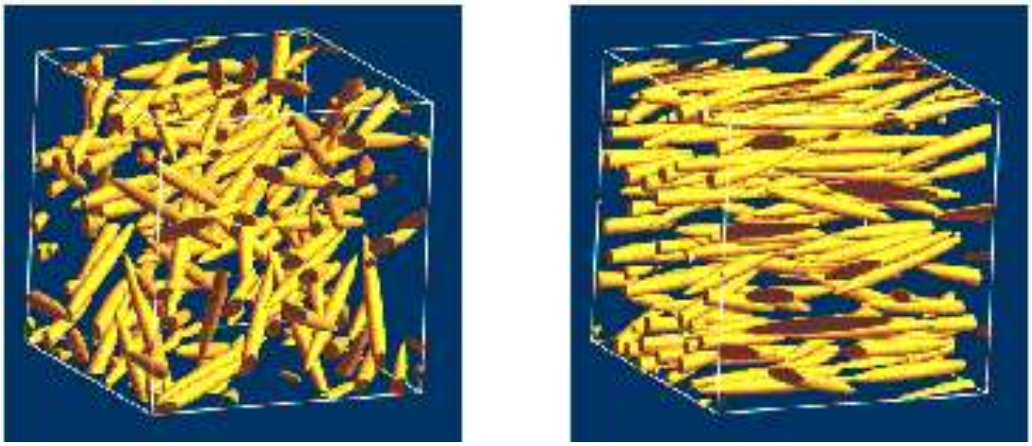

Fig. 2: Left: totally un-oriented fibers (λ_1=33%, λ_2=33%, λ_3=33%), right: strongly oriented fibers (λ_1=98%, λ_2=1%, λ_3=1%)

The distribution of the orientation tensor in a fiber reinforced plastic component can be simulated by an injection molding simulation. Commercial software tools are available as e.g. MoldFlow, which has been used also for this research project.

The FEMFAT Concept

Our software is a commercial fatigue life prediction tool developed at the Engineering Center Steyr, which is successfully in use at automotive companies, railway industries, mechanical engineering and some others since more than 15 years. FEMFAT assesses commonly linear elastic stresses analyzed by FEM (finite element method). Interfaces are provided to all common finite element pre- and postprocessors and solvers (NATRAN, ABAQUS, ANSYS, I-DEAS, PERMAS, MEDINA, etc.). The "influence parameter concept" used in our software calculates influence factors on local S/N curves for each influence factor listed above. Basic input material data are S/N curves of smooth un-notched specimens for alternating tension-compression loading (for stress ratio R = -1). These material S/N curves are modified locally at each node of the finite element mesh leading to local component S/N curves (see Fig. 3). This concept is originally based on the report "Synthetic S/N Curves" of Hück, Thrainer, Schütz [7, 8]. Then at each node of the FE-mesh a damage analysis is performed applying the linear damage accumulation rule of Palmgren/Miner.

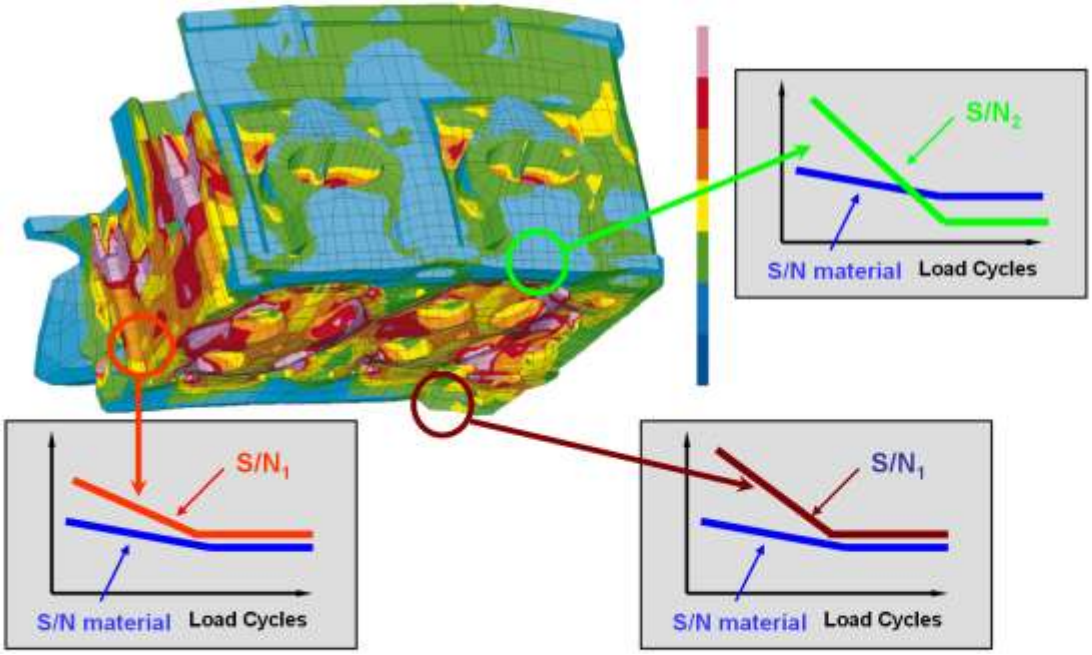

Fig. 3: The concept of local S/N curves: The blue lines indicate material S/N curves, which are locally modified in dependence on relative stress gradient, temperature, etc. (leading to read, brown and green line) for the analysis of the damage distribution on the component.

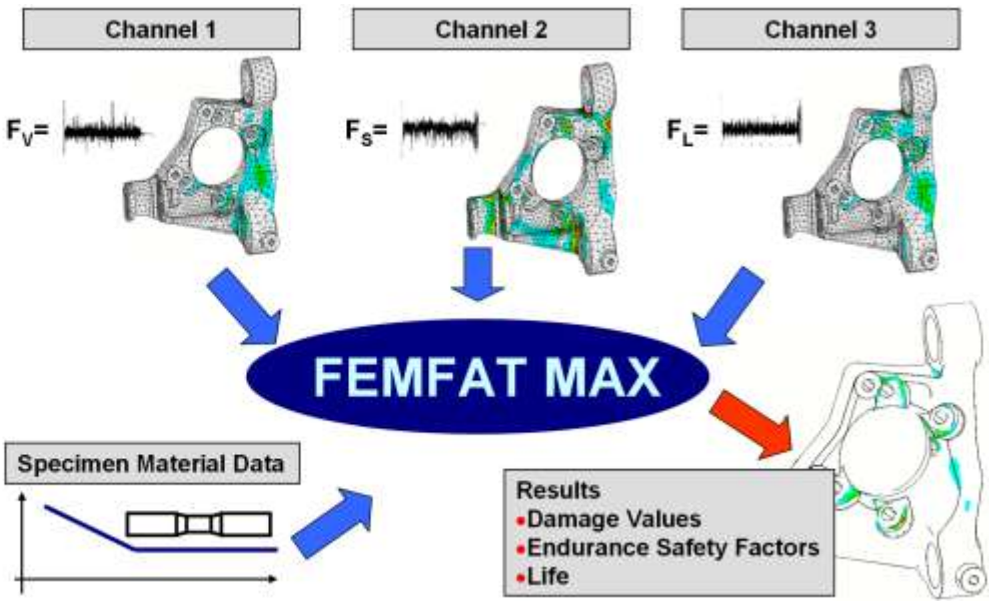

Fig. 4: Damage analysis of multi-axially loaded components

Our software is also able to deal with multi-axial and non-proportional random loadings (Fig. 4), where a critical plane method is applied [16-18]. Locally in each material plane a damage analysis is performed. The plane with maximum damage is assumed to be critical for fatigue failure and the corresponding damage value will be output as result at the considered FE-node.

For tri-axial stress states and rotating principal stresses, a major problem is the detection and counting of closed hysteresis loops in the stress strain path, which are representing damaging events. At the Engineering Center Steyr a relative simple method has been developed, which solves this problem [19]. Usually a rainflow counting procedure can be applied to the normal stress acting in material planes without any problems. This procedure gives good results for brittle materials as cast iron. But for ductile materials the shear or Mises stress is responsible for fatigue failure, for which in general a cycle counting procedure is not applicable because of the missing sign. This problem has been solved by introducing a time dependent correction factor for the normal stress, leading to an equivalent stress similar to the Mises stress, but equipped with a sign:

$$f = 1 + \left(1 - \frac{\sigma_{fl}}{\tau_{fl}}\right)\frac{\sigma_3}{\sigma_1} \tag{1}$$

The ratio of the tensile fatigue limit σ_{fl} to the shear fatigue limit τ_{fl} is a measure for the material ductility (1 = brittle, 1.73 = ductile). The ratio of the principal stress σ_3 with the minimum absolute value to the principal stress σ_1 with the maximum absolute value characterizes the type of loading (-1 = torsion loading, 0 = tension/compression loading, 1 = hydrostatic stress state). The advantages of this method are simplicity, efficiency and accuracy, because the exact material ductility and the loading type can be taken into account.

Extensions for Anisotropic Materials

Short fiber reinforced plastics behave strongly anisotropic. For the investigation of the anisotropy a lot of static and cyclic tests on different specimens have been performed at the University Leoben [6]. Fig. 5 shows S/N curves for a polyamide with 40 % glass fibers for tensile loading longitudinal and transversal to the fiber orientation. The standardized specimens were manufactured by injection into an appropriate mold, whereas the short specimens have been cut out from injection molded panels.

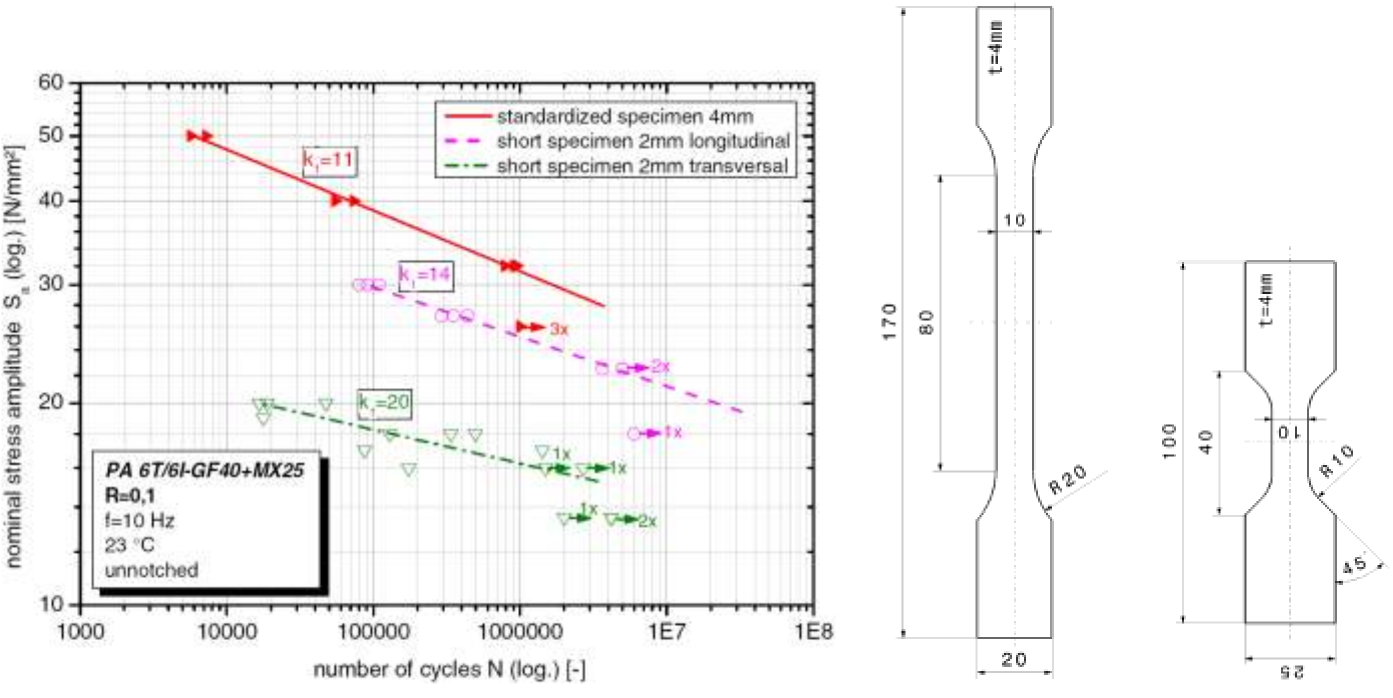

Fig. 5: Left: Influence of fiber orientation on fatigue behavior of PA 6T/6I-GF40+MX25, right: used specimens (k indicates the inclination of the s-n-curve)

Tests were done for R = -1 and R = 10 at a frequency of 10Hz. Higher frequencies lead to an incorrect result due to the heating of the material.

Static material parameters (Young's Modulus, ultimate strength, yield strength) and measured S/N curves for tension-compression loading longitudinal and transversal to the fiber orientation are basic material input data for fatigue analysis of anisotropic materials. For this purpose the existing critical plane criterion has been extended in this way, that in each plane a different S/N curves will be used for fatigue analysis depending on the orientation of the plane relative to the fiber orientation. But first, material parameters and S/N curve parameters (fatigue limit, slope and cycle limit) are needed in the principal anisotropy directions. For given shares of fibers λ_1, λ_2 and λ_3 these parameters can be determined by linear interpolation, see Fig. 6 on the left. The symbol w stands for any material parameter like Young's Modulus, ultimate strength, fatigue limit etc. w_1, w_2 and w_3 are the interpolated parameters in the three principal anisotropy directions. Next, material parameters have to be interpolated for a given plane specified by its normal vector **v**. When rotating the plane by 90 degree from one principal anisotropy direction $\mathbf{e}_1$ to another $\mathbf{e}_2$, a rather simple sinusoidal variation of all the material parameters $w_\mathbf{v}$ will be assumed:

$$w_v = \frac{w_1 + w_2}{2} + \frac{w_1 - w_2}{2} \cos 2\varphi \qquad (2)$$

Conversion into Cartesian coordinates and extension to three dimensions yield:

$$\frac{w_1 x^2 + w_2 y^2 + w_3 z^2}{\left(x^2 + y^2 + z^2\right)^{\frac{3}{2}}} = 1 \qquad (3)$$

The closed 3D-surface described by this equation is shown in Fig. 6 on the right. It is used for interpolation of static material parameters and S/N curves for a given material plane.

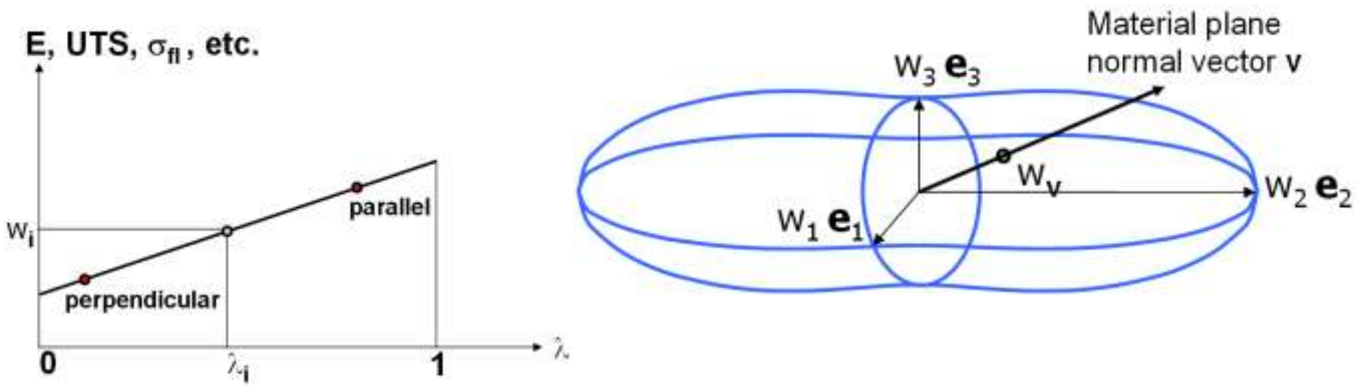

Fig. 6: Interpolation of material parameters, left: first in anisotropy principal directions from two measured values and given local shares of fibers λ_i, i = 1, 2, 3; right: secondly in a material plane

According to [1-2] also the linear damage accumulation rule of Palmgren/Miner has been extended for short fiber reinforced plastics by introducing an exponent *b*:

$$D = \left(\frac{n_1}{N_1}\right)^b + \left(\frac{n_2}{N_2}\right)^b + \left(\frac{n_3}{N_3}\right)^b + \cdots + \left(\frac{n_{i-1}}{N_{i-1}}\right)^b + \left(\frac{n_i}{N_i}\right)^b \qquad (4)$$

The exponent b was determined by tests with variable amplitudes and different load sequences by [1]. The results indicate that the rule of Palmgren/Miner provides a reasonable engineering estimate of the fatigue life of fiber reinforced plastics with an average value of b = 0.92.

Workflow – From Process Simulation to Fatigue Life Prediction

A lot of input data are needed for fatigue life prediction of short fiber reinforced plastics:

- The finite element structure including all nodes and elements. The finite element structure is originally created by the injection molding simulation tool. Although nowadays "2.5"-dimensional shell elements with several layers are more common for injection molding simulation, it was decided to use 3D solid elements for exact modeling of notches, which is essential for accurate fatigue life prediction. But the 3D structure from the injection molding simulation is not always optimal for structural stress analysis and fatigue life prediction, because it consists of a huge amount of rather small elements of almost the same size. For structural stress analysis usually rough meshes are sufficient, otherwise the calculation effort is too high. Only in notches very fine meshes are necessary. Actual developments take aim to map local material parameters (Young's Modulus, Poisson's ratio), orientation tensors and residual stresses from one given FE-mesh to another.
- Stresses resulting from external dynamic loads. It is essential to perform the stress analysis with local anisotropic material parameters (Young's Modulus, Poisson's ratio), which are a result of the injection molding simulation.
- Load histories for each force/moment acting on the component, as shown in Fig. 4.
- The fiber orientation tensor distribution from the injection molding simulation.
- The residual stress tensor distribution as a result of the injection molding simulation.
- Static material parameters and measured S/N curves for tension-compression loading both longitudinal and transversal to the fiber orientation.

A consistent and working simulation chain already exists, as shown in Fig. 7. It consists of the commercial software tools MOLDFLOW for injection molding simulation, ABAQUS for stress analysis with local anisotropic material parameters and FEMFAT for fatigue life prediction. For data transfer all relevant interfaces exist. Data files in MOLDFLOW .xml format and ABAQUS .odb format (or the predecessor format .fil) are used for data transfer. Also ANSYS can be used as FE-solver for stress analysis. In our software interfaces are available for ANSYS .cdb (FE-structure) and .rst (stresses).

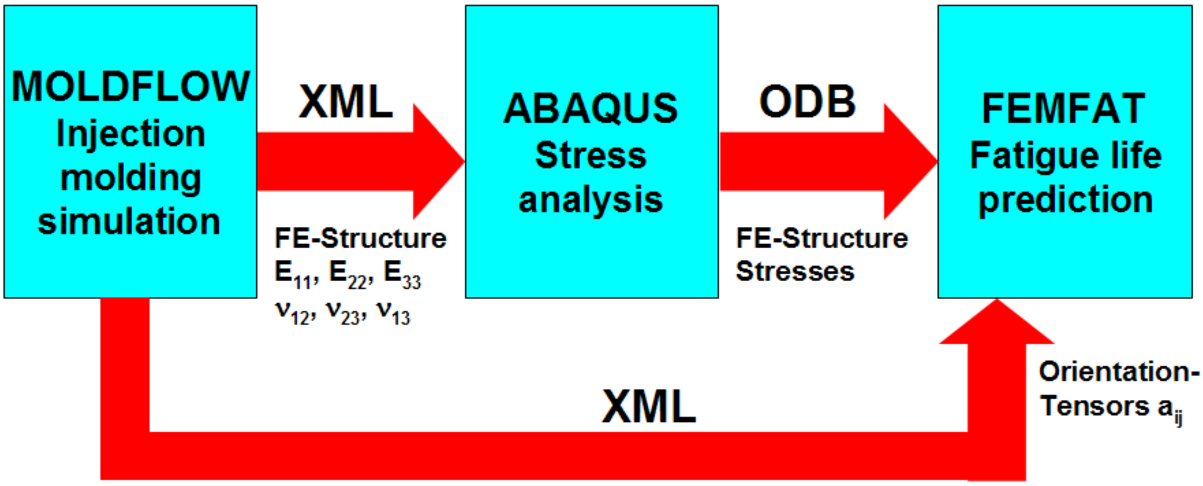

Fig. 7: Workflow and interfaces from process simulation to fatigue life prediction

Examples

Belt Pulley

As a component from the automotive industry, which is already in operation, a belt pulley has been analyzed and tested. For anisotropic stress analysis and fatigue life prediction the original mesh from the injection molding simulation has been used. Therefore the element size is rather small and the FE-mesh consists of 1.5 million (!) linear tetrahedron elements, see Fig. 8 left hand side. The right hand side shows the model for injection molding simulation with MoldFlow including cast channels and the melting entries. In Fig. 9 the stress amplitude distribution simulated with ABAQUS and the damage distribution simulated with FEMFAT can be seen. Also tests have been performed as shown in Fig. 10. The fatigue life analysis was able to predict correctly the critical location, where the crack initiates, and also the absolute value of the predicted fatigue life was within the range of dispersion.

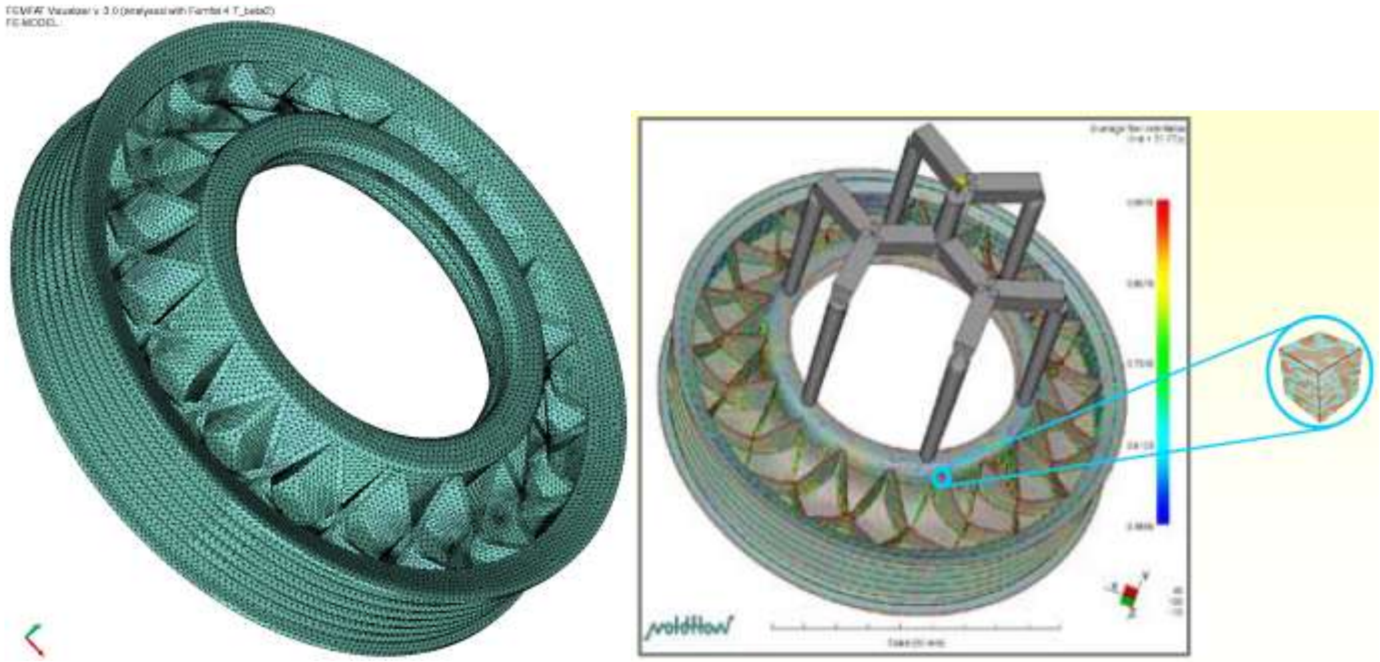

Fig. 8: Left: Finite element model of a belt pulley consisting of 1.5 million elements, right: Injection molding simulation with MoldFlow

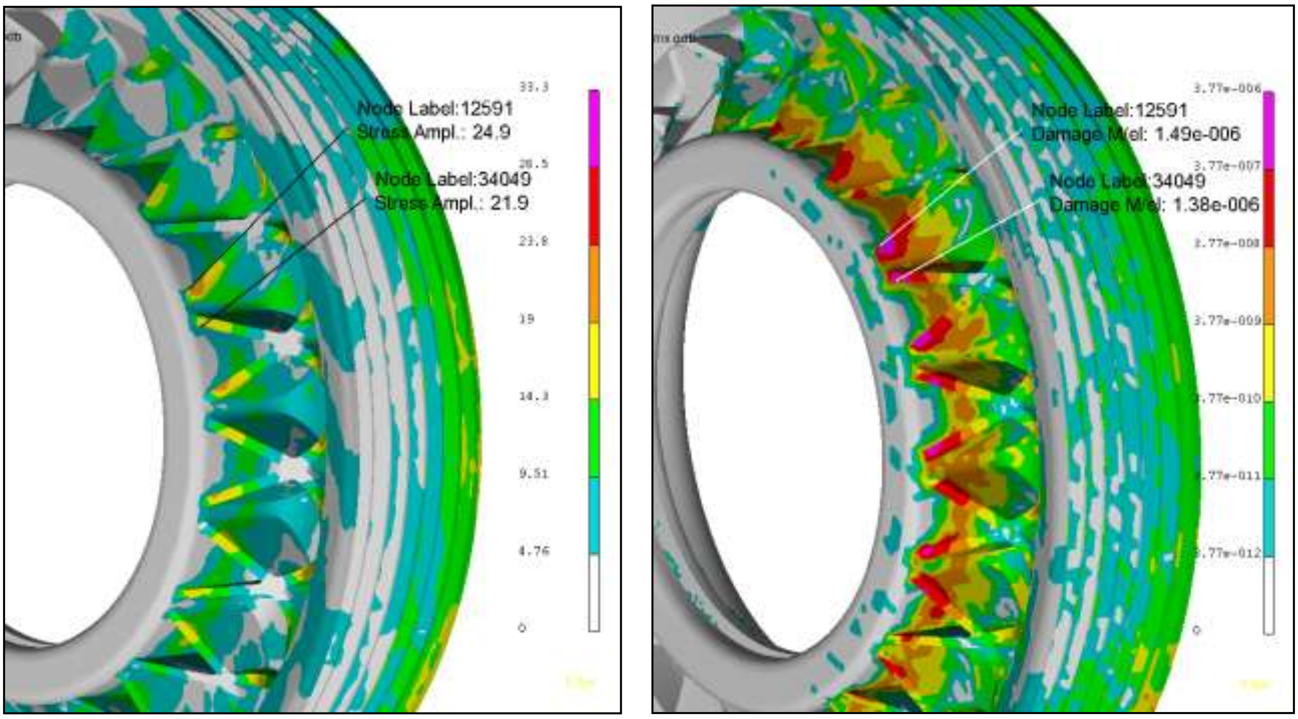

Fig. 9: Distribution of stress amplitude simulated with ABAQUS and damage distribution simulated with FEMFAT, stress amplitude [N/mm²]

Fig. 10: Test bench for a belt pulley [20]

Ring Spanner

Next a ring spanner is presented (Fig. 11). The mesh consists of about 200.000 elements. Analyses with anisotropic material and two isotropic materials for best and worst case have been performed. It was found, that there is factor of 7 between the fatigue life for best and worst case. The result for anisotropic material is settled between best and worst case.

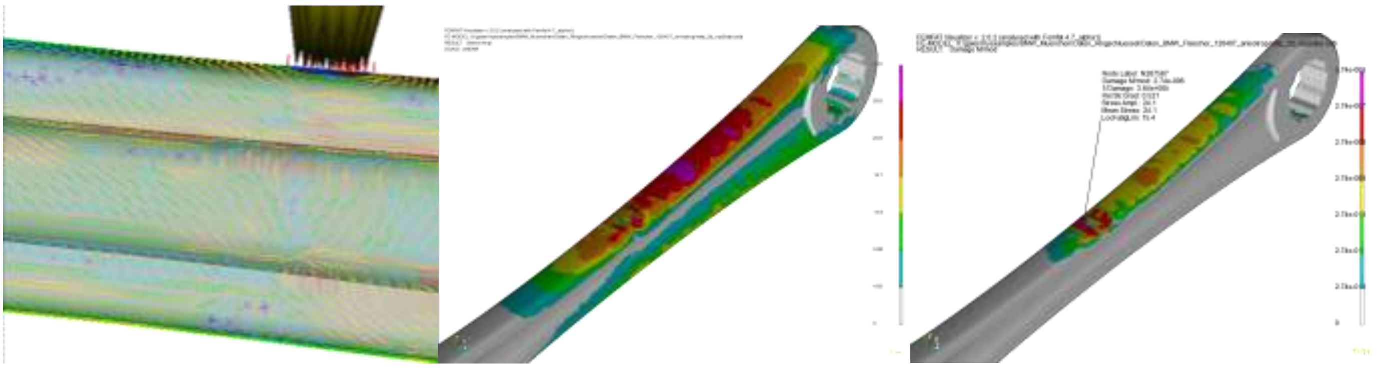

Fig. 11: Ring spanner, left: average glass fiber orientation at injection location, middle: distribution of stress amplitude simulated with ABAQUS, right: Damage distribution simulated with FEMFAT

Summary and Outlook

It has been shown, that fatigue life prediction of short fiber reinforced plastic components based on S/N curves is possible by taking into account the fiber orientation and distribution resulting from an injection molding simulation. The presented simulation process works well and has been installed at BMW and ECS.

The research project will be continued, and other influences on fatigue life will be investigated:

- Notches
- Moisture absorption
- Environmental media (glycol/water)
- Joint lines

But there is still no practical solution available for mapping of injection molding simulation results (local material parameters as Young's Modulus, fiber orientation tensor, residual stresses) onto other FE-meshes for structural stress analysis. A lot of efforts take aim to provide a practical solution in the near future.

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