Cumulative Failures Prevention

The Influence of Varying Frequency and Load Level on the Fatigue Life of Short Glass Fiber-Reinforced Technical Thermoplastics

Short glass fiber-reinforced plastics are exposed to complex load cases during the operating time. Therefore, the influence of alternating load and frequency in the form of load spectra on material fatigue is investigated and an integrative computational method for structural design is presented. With this practical approach, a fast fatigue life estimation is possible.

Successful and sustainable use of short glass fiber-reinforced thermoplastics depends on material-appropriate dimensioning methods that realistically describe the mechanical behavior and can predict material failure. In practice, proof of fatigue strength is provided by complex, cost-intensive tests on close to series production components under real load. This procedure has the disadvantage that the development process is already very far progressed at the time of testing and design changes are accompanied by substantial expenses. However, numerical calculation methods provide a solution to this challenge.

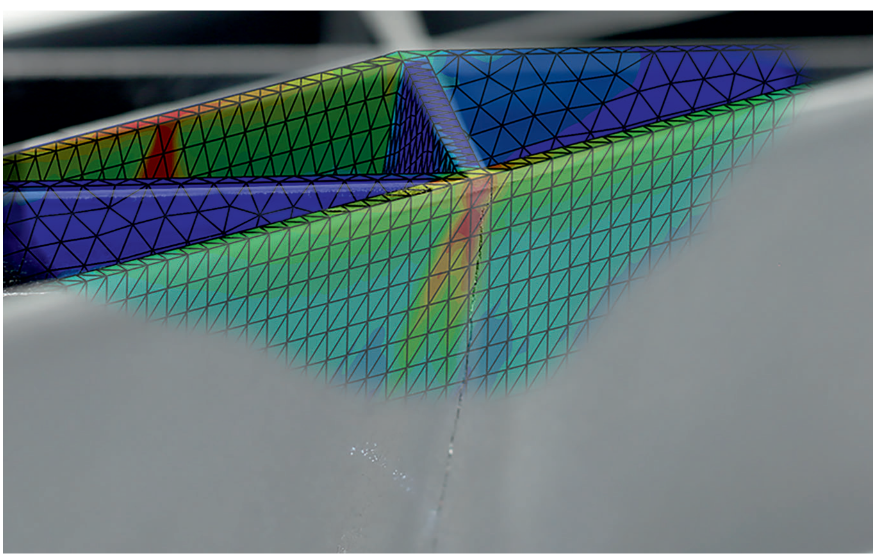
Fatigue models based on material Woehler curves are used for the fatigue life predictions [1]. These data are generated in dynamic-cyclic tests under idealized and constant test conditions. However, in real applications, complex load cases occur, which are characterized by varying mechanical loads over time with regard to load level and frequency. With the use of damage accumulation hypotheses, it is possible to develop calculation methods for complex load/time curves [1].

Frequency Influence on Fatigue Life

A short glass fiber-reinforced polyamide 6 of type Zytel 73G15HSL from DuPont de Nemours (Deutschland) GmbH, Neu-Isenburg, Germany, is used for the tests. The mechanical properties and thus the fatigue behavior of short glass fiber-reinforced plastics depend, among other things, on the fiber orientation prevailing in the material [2–4]. Therefore, test specimens with different main fiber orientation are taken from injection-molded plates.

To determine the influence of the frequency, the fatigue tests are carried out at 1 Hz, 5 Hz and 15 Hz (**Fig. 1**). The fatigue characteristics differ depending on the load frequency. The results between 1 Hz and 5 Hz show a similar trend idealized as linear. The Woehler lines deviate at load cycles of approximately 10^4, which results in a greater number of bearable load cycles at the higher frequency of 5 Hz.

In contrast, the Woehler line for 15 Hz is characterized by a regressive curve and the number of cycles to failure is up to a maximum of two decades lower for the same stress levels than for the 1 Hz and 5 Hz tests. The same trend can be observed when looking at the results for the transverse oriented samples. The Woehler lines for 1 Hz and 5 Hz are characterized by degressive progressions and the Woehler line for 15 Hz again by a regressive behavior. In contrast to the longitudinal test specimens, the Woehler lines distinguish more between 1 Hz and 5 Hz. A transversely oriented test specimen with a load of approx. 44 N/mm^2 withstands approximately 10^3 cycles at a 5 Hz load and approximately $2.8{\cdot}10^4$ load cycles at 5 Hz and thus exhibits a fatigue life that is over a decade higher.



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Load Spectra Effect the Fatigue Life

In order to investigate the effects of varying load and frequency, damage accumulation tests are performed in the form of exemplary load spectra. The exemplary load spectra consist of four phases, whereby the frequency f and stress F_O are varied in three levels. The number of cycles is defined for each phase based on the linear damage parameter $d_i = n_i/N_i$. Here, n_i is the number of cycles applied to the specimen in the respective phase. The number of cycles to failure N_i can be determined from the previous Woehler experiments according to the frequency- and load-level. The first phase is used for mechanical conditioning of the test specimens, since it is principally the first load cycles that can cause initial damage to the material (d_1=0.10) [5]. In the two subsequent phases 2 and 3, an identical damage parameter of d_2=d_3=0.25 is defined. The fourth and thus last phase is used for evaluation.

The results of the exemplary load collectives for the evaluation phase 4 are shown in **Figure 2.** First of all, it is clear that there are test sequences (1 and 7) for both longitudinal and transverse orientation, where the evaluation phase is not always reached and the material fails prematurely. Furthermore, it can be stated that the scattering of the measurement results is differently pronounced depending on the test blocks and the fiber orientation. In total, the material test results for the longitudinal and transverse direction exceed the number of targeted load cycles in five of eight exemplary load spectra. For the case with longitudinally oriented samples, the descending test sequences (1, 3 and 5) achieve higher numbers of bearable load cycles. In comparison, the transversely oriented test specimens show an inverted pattern. The increasing test sequences are characterized by higher numbers of load cycles till failure.

Numerical Assessment of Fatigue Using Master Woehler Lines

In order to be able to dimension the fatigue life of structures made of short glass fiber-reinforced plastics in compliance with the material, the fiber orientation in the molded part and the resulting mechanical properties must be considered in the numerical calculation [4]. Therefore, an integrative simulation chain is developed consisting of a process and structure simulation. Sigmasoft Virtual Molding from Sigma Engineering GmbH, Aachen, Germany, is used as injection molding simulation software. This software calculates the local fiber orientation of the molded part and transfers it to the structure simulation in the Abaqus environment, Dassault Systèmes, Vélizy-Villacoublay, France. A quasi-static simulation is carried out and a static stress factor r according to Tsai and Hill is calculated depending on the applied structural stress [8]. The resulting static stress factor correlates to the anisotropic material stress, but does not contain any orientation information. In order to be able to estimate the fatigue life with this variable, the previously determined fiber orientation-dependent Woehler curves are normalized according to the corresponding orientation by means of quasi-static strengths and then averaged. As a result, a master Woehler curve is obtained for each frequency, which is independent of the fiber orientation [6]. This provides the correlation between the dynamic stress factor r_{dyn} and the number of cycles to failure (**Fig. 3**).

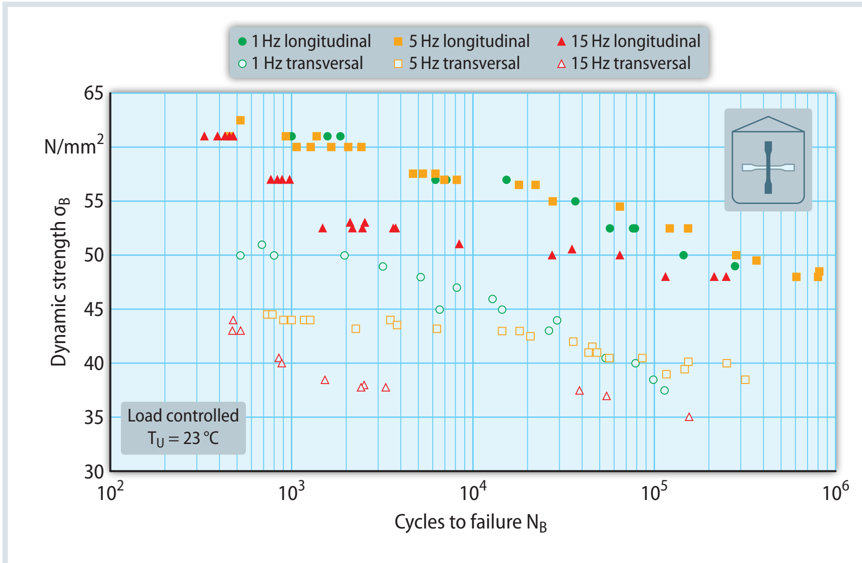

Fig. 1. Fiber orientation dependent fatigue data from Woehler tests at stress frequencies of 1 Hz, 5 Hz and 15 Hz Source: IKV, graphic: © Hanser

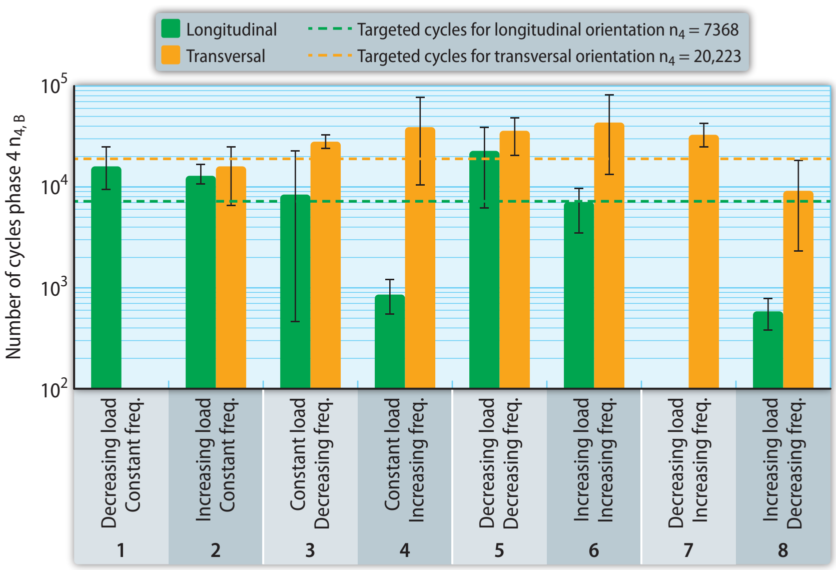

Fig. 2. Comparison of the number of bearable cycles achieved in the evaluation phase

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Consideration of Load/Time Sequences for Numerical Fatigue Prediction

The common damage accumulation hypotheses for the calculation of varying loads during dynamic-cyclic exposure are based on the relationship between the number of load cycles applied and the number of cycles to failure at the corresponding constant test frequency and load. Using a classification method » such as Rainflow analysis, an equivalent load spectrum can be determined from a real load/time pattern [1, 7]. For each block load of the load spectrum, a structural simulation is subsequently carried out at the corresponding load level F_i and the required number of fatigue cycles is determined. With the applied number of cycles n_i, the partial damage d_i is calculated and summed up with a damage accumulation hypothesis. If the total damage D remains below 1, then the component endures the targeted fatigue load.

To verify the presented method, three exemplary load spectra are applied to test components with a ribbed design. The model component is subjected to dynamic-cyclic testing in a 3-point-bending experiment, whereby the critical areas of the component are subjected to tensile stress. The component tests are carried out in the same manner as the load spectrum experiments

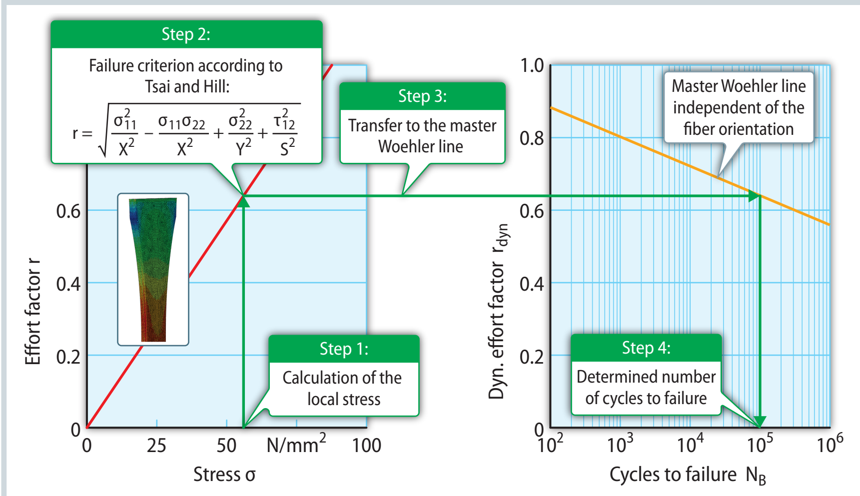

Fig. 3. Master Woehler line concept for calculating the number of cycles to failure

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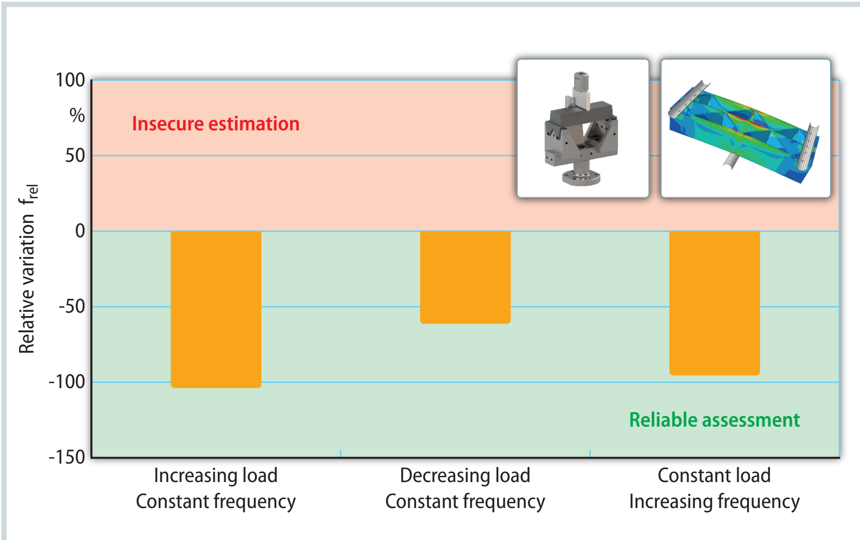

Fig. 4. Verification of the presented calculation method using a ribbed component in a 3-point-bending experiment Source: IKV, graphic: © Hanser

at specimen level. **Figure 4** shows the estimation of the component fatigue life using the damage accumulation hypothesis according to Palmgren and Miner [8, 9], which was calculated with the integrative simulation method. The numerically determined fatigue life of the ribbed component is approx. 61 to 103 % below the actual number of bearable load cycles, which means that the fatigue strength is estimated to the safe side. Thus, the simulation methodology was successfully applied and verified on a practice-oriented component.

Conclusion

In the presented studies it could be shown that the experimentally determined fatigue data show a non-negligible frequency dependence for the characterized material. Furthermore, it was found that load sequence effects can occur with varying load levels and frequencies, which can have a negative effect on the number of bearable cycles.

With the integrative computational approach presented here, acceptable predictions can be made regarding the number of ultimate load cycles, both for a constant and for exemplary load spectra, using master Woehler lines and a quasi-static structure simulation with an anisotropic material model. This practical approach enables a fast fatigue strength assessment on the component level and can be used to support the engineering process of complex structural components. ■

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Acknowledgments

The research project 19419 N of the Forschungsvereinigung Kunststoffverarbeitung was sponsored as part of the „industriellen Gemeinschaftsforschung und -entwicklung (IGF)“ by the German Bundesministerium für Wirtschaft und Energie (BMWi) due to an enactment of the German Bundestag through the AiF. We would like to extend our thanks to all organizations mentioned.

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