Probabilistic lifetime prediction with application to high-performance p-aramid fiber

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Summary English

This thesis is on modelling the lifetime of Twaron p-aramid fiber, a high-performance light-weight fiber. High performance fibers and fiber composites are well-known for their strength and high modulus properties, enabling competition with conventional steel wire solutions. For industrial products (ropes, pipes, optical fibers) manufactured from or reinforced with fibers, both strength and expected lifetime of the fiber are important. Even if synthetic fibers are loaded far below their tensile strength they fail within finite time ('creep rupture'). The total time a fiber can withstand a constant load is called *the time-to-failure*, which depends on the applied load, temperature and material properties. Time-to-failure is a stochastic parameter and hence is represented by a distribution. Time-to-failure of Twaron p-aramid fibers is satisfactorily described by a Weibull distribution.

In the laboratory, constant-load experiments on fibers subjected to low loads, representative for practical applications, are not feasible because such experiments would last for many years or even decades. Instead, time-to-failure is experimentally observed for fibers subjected to high constant loads, corresponding to short times-to-failure. Long-term time-to-failure is then estimated by extrapolation of the short time-to-failure data.

In this thesis we explore two ways of extrapolation: simple regression analysis and maximum likelihood estimation. Instead of performing short time-to-failure measurements in the laboratory, time-to-failure data are randomly drawn from an appropriate Weibull distribution. By means of Monte Carlo simulations the procedure for estimation of long-term time-to-failure is mimicked. Each Monte Carlo simulation consists of random time-to-failure drawing (replacing short-term experiments) followed by regression or maximum likelihood estimation to obtain the time-to-failure distribution at low load. We demonstrate that the natural variability in fiber time-to-failure influences the quality of long-term time-to-failure estimation. For fibers with highly variable time-to-failure, estimation is less reliable and more conservative safety factors are necessary. Prediction of the time-to-failure variance is biased towards a narrower distribution.

Not only should fibers survive their economic lifetime with high probability, mechanical properties such as strength should also remain at a high level, for instance to be able to cope with peak stresses during service life.

We measured residual strength of preloaded Twaron p-aramid fibers. Residual strength stays close to the virgin strength level, even if loading is continued almost up to the moment of breaking. In the thesis we also show that an important class of material failure models is not able to capture the residual strength properties of Twaron p-aramid fiber: these models statistically significantly underpredict residual strength of these fibers.

For modelling the lifetime of high-performance fibers or other materials, damage models can be used. These models describe how damage builds up in a fiber during an arbitrary load program. A threshold accumulated damage level determines the (generally deterministic) moment of failure. Probabilistic damage models, a small minority within the group of damage models, reckon with the stochastic nature of time-of-failure. From probabilistic models, we derive a probability that the fiber will fail, provided the current level of damage and current load are known.

Many existing models are based on 'linear damage theory': damage contributions of pieces of the load program add up linearly to obtain the overall damage level, which determines how far away the fiber is from breaking. For these models, 'load order' is irrelevant for damage accumulation and hence the moment of failure. Many materials, including p-aramid fibers, are known to exhibit more complex failure behavior. We are not aware of any existing probabilistic model which does not conform to 'linear damage theory'.

In this thesis we construct two classes of probabilistic models for which 'load order' profoundly affects time-to-failure. The models are tuned with easy measurable fiber properties such as the virgin strength and the time-to-failure at constant load. We examine both models for single step constant load programs. During such program, fibers are sequentially loaded to two loads, with a single, rapid load switch at a specified time. Single step constant load programs are particularly useful to investigate materials' failure behavior because they are experimentally easy and effects of 'load order' on survival time are well observable. We measured time-to-failure of Twaron p-aramid fibers subjected to several series of single step constant load programs. The measurements cannot be captured by any of the models analyzed in the thesis. For one of the experimental series, fiber failure properties even improved after the fibers were subjected to a preload. Such failure behavior cannot be explained by any model which assumes that damage accumulation is a non-negative function of the current load level.