Tensile strength of single fibers: test methods and data analysis

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ABSTRACT

The load-bearing capacity of fiber-reinforced materials is to a large extent determined by the tensile strength of the fibers. The latter typically exhibits marked scatter thus warranting a statistical treatment. Weakest-link character of fiber failure is reflected in the commonly used Weibull two-parameter distribution of fiber strength:

$$P(\sigma) = 1 - \exp\left[-\frac{l}{l_0}\left(\frac{\sigma}{\beta}\right)^{\alpha}\right] \tag{1}$$

where σ is the tensile stress at fiber failure, α, β designate Weibull shape and scale parameters, l stands for fiber length, and l_0 is a length unit. There is, however, growing experimental evidence that Eq. (1), while accurately describing strength scatter at a fixed fiber length, may not comply with the observed strength variation with fiber length. Instead, the modified Weibull distribution:

$$P(\sigma) = 1 - \exp\left[-\left(\frac{l}{l_0}\right)^{\gamma}\left(\frac{\sigma}{\beta}\right)^{\alpha}\right] \tag{2}$$

with $0 \le \gamma \le 1$ is found to better agree with strength data of inorganic (glass, carbon) and natural organic (flax, jute, wool) fibers.

The origin of Eq. (2) and physical interpretation of its parameters is discussed. The most common strength test methods, fiber tension test (FTT) and fiber fragmentation test (FFT), are applied to evaluate Eq. (2) parameters. It is demonstrated, by an example of E-glass fibers, that FFT provides sufficient information to accurately estimate the parameters of the modified Weibull strength distribution for brittle linear elastic fibers. By contrast, pronounced scatter in the mechanical response of natural fibers, e.g. variability of modulus of elasticity, is shown to complicate the relation between the limit strain distribution provided by FFT and the fiber strength distribution obtained by FTT.

Assuming that the strength of agrofibers is governed by mesoscopic cell wall defects, fiber strength distribution in terms of defect density and severity is derived and found to approach Eq. (2) in the limit of a high defect density. Identifying the defects with kink bands in flax fibers, strength distribution Eq. (2) parameters are determined based on FTT at a fixed fiber length and kink band density measurements by optical microscopy. Thus obtained distribution function is further applied to successfully predict flax fiber strength at different lengths and the strength of flax fiber reinforced polymer matrix composites. The results obtained suggest that the modified Weibull distribution accurately describes the strength of both, inorganic and natural organic fibers. The strength testing can be made less tedious by combining FTT with (or replacing by) FFT.