X-RAY TOMOGRAPHIC INVESTIGATION OF STOCHASTIC DAMAGE IN POLYMER COMPOSITES

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The major objective of the work presented in this lecture was to gain so far unavailable experimental insight into the physics of failure of unidirectional polymer-based composite materials. Under a tensile stress, such model composites eventually fail in a complex stochastic fashion involving random fiber breaking at weaker sites (reflecting the statistical strength variability of thin fibers) and fracture of neighboring fibers by way of stress transfer through the matrix. Damage proceeds by the nucleation and growth of clusters of adjacent breaks (Figure 1), until one of those clusters reaches a critical size, at which point catastrophic failure occurs.

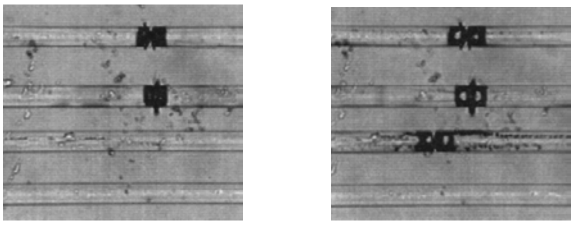

Figure 1: Growth of a cluster of adjacent breaks in a quartz/epoxy composite (2-dimensional view). The fiber diameter is 9 μm.

Smith[1] proposed that if the fracture strength σ of a single fiber of length δ can be modeled by a Weibull probability distribution function $F(\sigma) = 1 - \exp\left[-\delta(\sigma/a)^b\right]$, where a is the scale parameter (correlated with the average strength) and b is the shape parameter (related to the variability of the distribution), then the probability of failure of the unidirectional composite material based on N parallel fibers is given by

$$F_N(\sigma, L) = 1 - \exp\left[-L\left(\frac{\sigma}{\alpha}\right)^\beta\right]$$

thus again a Weibull distribution, where α and β are the scale and shape parameters of the composite. One powerful aspect of this simple model is that the Weibull parameters of the parent single fiber and those of the composite are mathematically related: (i) $\alpha = aN^{-1/\beta}\psi(.)$ where $\psi(.)$ is a complex function of the geometry, the load sharing rule, the load concentration factors and material parameters; (ii) $\beta = k*b$, a particularly straightforward relationship, where k* is the critical size of the cluster of adjacent broken fibers at failure. This approach thus provides a link between microscopic variables –at the level of the single fiber- and the macroscopic strength behavior of the composite. Batdorf[2] has proposed a slightly different approach to this problem. It is in principle possible to experimentally verify this theory by means of model 2-dimensional composites and indeed several studies have appeared in the literature[3-10]. An evident advantage of experiments with 2-d microcomposites is that using a video camera attached to a microscope, one is able to monitor the fracture process and measure the size of the break clusters at each stress level. The experiments are not quite conclusive, however, mainly because several inherent problems arise. One of them is the fact that it is impractical to prepare 2-d composites with more than 15 to 20 fibers, and it is certainly possible that the critical cluster size k* is larger than this number. Another problem is that the stress state in a 2-d composite is quite different from that in a real 3-d composite. With the latter, however, it is evidently impossible to monitor the fracture process by video recording because of the very large amount (thousands) of fibers present in a bundle, and because of the 3-d configuration.

Thus, the aim of our recent experiment experimental performed at the ESRF facilities, was to use X-ray tomography at high resolution (2 μm) with unidirectional bundle-reinforced 3-d composites ('minicomposites'). The specimens, which are as close as possible to real-life composites, were tested under in-situ axial tension, and the nucleation and growth of damage was monitored by scanning along the specimen length. The evolution of the size and number of clusters of breaks was recorded until final failure occured. The aim of this experiment was to allow us to quantify the composite fracture process in detail, and verify or refute the validity of the Smith/Batdorf stochastic fracture concepts. The matrix was a soft DGEBA epoxy with a failure strain of approximately 6 percent. Quartz fibers were used, since we have had good success with it in the past when performing single-fiber fragmentation tests.

We observed a quantitative discrepancy between the experimental value for the number of broken adjacent fibers forming the critical cluster, k*, and the value predicted by the Smith-Phoenix model: the value of k* from our experiments is about 3 times larger than the predicted value. We argue that while k* in the model is related only to the variation in strength, the formation of a critical cluster in 3-d composites is a complex process, and k* most probably depends on other factors besides the variation in strength. This lecture presents our experimental results, including an estimation of critical cluster size, k*, and our attempt to understand the failure physics of 3-d unidirectional composites, based on direct tomographic evidence.

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