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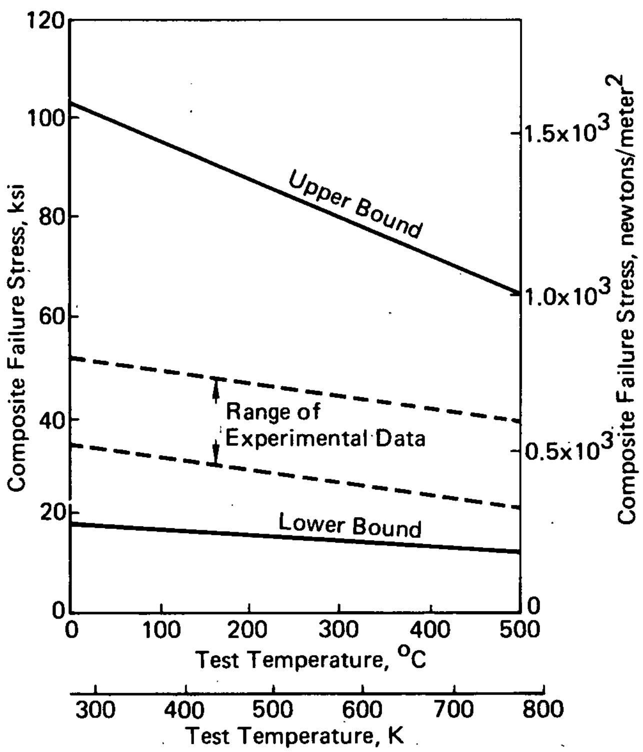
New Understanding of Fiber Composite Materials

Recent contributions have been made to the theoretical and empirical understanding of composite materials—fibers of suitable materials embedded in a plastic or metal matrix—which comprise a new area



Tensile Strength of Alumina Whisker – Aluminum Composites as a Function of Temperature

of materials technology, with important potential for materials chemists and mechanical and structural engineers.

The high tensile strength and ease of forming are important advantages of filamentary composites. However, an understanding of their fracture mechanics is basic to safe, efficient utilization in structural design. A statistical bounding approach to the problem provides this understanding. Comparison shows that the bounds are in good agreement with data from a variety of fiber-matrix systems, and that they can be used to interpret strength data and to provide information on fracture behavior leading to improved strength.

The nonuniform strength of the commonly used fibers (such as boron, graphite, glass, alumina, silicon carbide, etc.) has significant effects on the strength of composite materials. The fracture of a single fiber can result in matrix cracks which may propagate through surrounding fibers, triggering a "weakest link" mode of failure. The expected stress at which the first fiber break will occur is therefore a lower bound on expected composite strength.

Many materials do not fail in the weakest link mode. In such materials, each scattered fiber break can be thought of as a nucleus for the propagation of fiber breaks. The stress concentration factors increase with the number of broken fibers, and the composite enters a "fiber break propagation" mode of failure. A lower bound on this failure mode is the expected stress at which the first overstressed fiber will break.

Another failure mode, associated with the inability of an entire cross-section to resist an applied load, can be used as an upper bound on composite tensile strength.

At least for certain fiber-matrix systems studied, a strong bond may result in a lower tensile strength than that obtained with a weaker bond. Presumably, a strong bond will result in improved transverse properties, indicating that there may have to be a tradeoff between tensile strength and transverse strength for some fiber-matrix systems.

(continued overleaf)

The figure shows the experimental and predicted strength as a function of the temperature of an alumina-whisker-in-aluminum composite. Note that the slope of the experimental data follows that of the lower bound more closely than that of the upper bound.

The classical Griffith-Irwin-Orowan theory of crack propagation, which is concerned only with homogeneous materials, is apparently not adequate for explaining the mechanics of failure in a notched unidirectional composite subjected to tensile load in the fiber direction. In composites, fiber debonding, matrix and fiber plasticity, and scatter in fiber strength all affect crack propagation.

Since the fibers are the main load carrying elements, a composite can carry load even though the matrix is completely fractured. Many fibers in a matrix can be fractured while the matrix remains intact. In either case, crack length is essentially undefined. Cracks in the matrix parallel to the fibers, and debonding of fibers, often present a failure mode not covered by the conventional approach.

If a fiber breaks in a thin plate consisting of a single layer of unidirectional fibers in an elastic matrix, the load is transmitted through the matrix to adjacent fibers. These are subjected to an increase in the average stress. When this stress reaches the ultimate strength of the fibers (assumed to be uniform), the one at the root of the notch will fail. The stress in the next intact fiber becomes greater than the ultimate fiber strength, it too fails, and a chain reaction failure occurs.

Studies indicate a drastic reduction in the strength of such composites if only a few fibers are cut. For example, a central notch that cuts only four fibers in an infinite sheet reduces the strength by over 50%, and only two fibers cut at the edge of a sheet will produce the same effect.

Not all fiber composites fall within the elastic matrix category. Where an inelastic matrix is used, stress concentrations in the vicinity of the notch root may cause fiber debonding or matrix fracturing parallel to the fibers. Once this phenomenon begins, small increments of applied load result in a large debonded or fractured region. Such debonding or cracking results in a drastic reduction of the maximum load concentration factor in adjacent, unbroken filaments.

The notch sensitivity of a material can be significantly reduced by providing a fiber-matrix bond that will fail before adjacent fibers are broken due to load concentrations. However, the adverse effects of fiber debonding on transverse properties must be taken into account.

The effect of matrix plasticity on load concentrations in a monolayer composite with one broken filament was investigated, with the matrix assumed to be elastic perfectly-plastic. The results indicate that, for the same load ratio, fiber debonding or matrix splitting results in a greater reduction in the maximum load concentration factor than does matrix yielding.

In the foregoing cases, in which the fibers have a unique ultimate strength, the failure of the notch-root fiber results in the propagation of fiber breaks, unless debonding occurs. However, if there is scatter in fiber strength, this is not necessarily true. When one of the notch-root fibers breaks, there is a finite probability that a nearby fiber will be able to resist both the steady state and dynamic stress concentrations resulting from the fracture of the first fiber. The probability of such failure constitutes a lower bound on the probability of failure due to crack propagation from a central or edge notch.

Although matrix plasticity results in a greater probability of failure than does matrix elasticity, this negative effect is generally overshadowed by the reduction in load concentration factor. In the case of debonding or matrix splitting, this reduction is even more pronounced. In the limiting case, the notch-root fiber has the same probability of failure as any fiber in the composite; i.e., there is no tendency for the notch to propagate.

The stress necessary to propagate a notch may be higher than the failure stress level at which an unnotched composite will fail. A long specimen with many fibers and a shallow notch will probably not fail as a result of a crack propagating from the notch. To the contrary, it can be expected that a fiber will break at some arbitrary point in the specimen, triggering failure, before a stress level is reached that is high enough to propagate a crack from the notch.

Note:

Requests for further information may be directed to:

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No patent action is contemplated by NASA.

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