Literature Review

Modeling Stiffness Loss in Boron/Aluminum Below the Fatigue Limit

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This report focuses on a problem that was also addressed by Johnson in a more general paper [1]. It begins from the observation that boron/aluminum composites can develop significant internal matrix cracking even when cycled below the fatigue limit. The cracking causes stiffness reductions of as much as 40% in quasi-isotropic laminates, for example. Johnson discusses a model for calculating that change and uses data from 6061 aluminum matrix composite material reinforced with 0.14-mm-diameter boron fibers. Data from five laminates tested previously ([0, 90]_2s, [90, 0]_2s, [0, ±45, 90, 0, ±45, 90]_s, and [0, ±45, 90]_s) and the new laminates ([0, ±45]_s, [0, ±45]_s, and [±45, 0, ±45]_s) are reported. Load and strain controlled tests are included.

Johnson begins by making the point that the shakedown limit (below which only elastic strains occur in the constituents after the first few cycles) is considerably below the fatigue limit for these materials. The shakedown range S_{sh} can be calculated as the width of the interior yield surface (formed by the superposition of lamina yield surfaces for a given laminate) in the direction of loading.

Above the shakedown limit, matrix cracking was observed. The progress of damage was followed by recording the laminate stiffness as a function of applied cycles for different applied load amplitudes. (Fiber failure did not appear until load levels near the fatigue limit.)

Referring to Fig. 1, when the cyclic stress range S exceeds the shakedown range S_{sh}, the matrix is assumed to respond as an elastic-perfect plastic material along the dotted line (for the first cycle) which ends in \sigma_m where \sigma_m equals half the shakedown strain range S_{sh}/2E_0 (where E_0 is the initial undamaged laminate modulus) times the undamaged matrix modulus E_m, that is

\[
\sigma_m = \sigma_{sh,m} = (S_{sh}/2E_0) E_m
\]  

When cracks form in the matrix and open on tensile excursions of the applied load, the hysteresis loop closes to the solid line in Fig. 1. For a given total strain range \Delta \varepsilon the effective tensile modulus of the matrix E_{eff,m} can be written

\[
E_{eff,m} = \sigma_{sh,m}/\Delta \varepsilon - \Delta S_{sh}/2E_0
\]  

where

\[
\Delta S_{sh}/2E_0 = \Delta \varepsilon_{comp}
\]  

which is the compressive strain range of the matrix. This modulus is entered into a laminate analysis to obtain the laminate tensile modulus, which is then used to estimate the secant modulus for the laminate. This process is shown in Fig. 2.

FIG. 1—Decreasing tensile matrix response and increasing 0° fiber stress as the laminate attains a saturation damage state. Dashed line is initial state, solid line is saturation damage state.

FIG. 2—Correlation between experimental results and model predictions for [0, ±45]_s laminate after 500 000 fatigue cycles. Squares are stress-controlled results, and circles are strain-controlled.
total load (or strain) cycle $E_{SDS}$. The laminate stress-strain relation is stated as

$$\Delta S = (\Delta e_{\text{comp}}^{\text{m}})E_0 + (\Delta e - \Delta e_{\text{comp}}^{\text{m}})E_{SDS}$$  \hspace{1cm} (3)$$

from which $\Delta S$ is calculated for strain-controlled tests, or $\Delta e$ is calculated for stress-controlled tests. The laminate secant modulus prediction is then

$$E_S = \Delta S / \Delta e$$  \hspace{1cm} (4)$$

Figure 2 shows a strong correlation between experimental and predicted results for the $[0, \pm 45]_s$ laminate. Other comparisons show comparable accuracy.

This report is a thorough and sound contribution to an important subject. While many of the calculations are based on simplified idealizations, the concepts are based on experimental observations and mechanistic representations that can support more sophisticated treatment in the future. Moreover, the generality of the approach has been demonstrated and several limitations clearly identified. The model as presented is a useful contribution.

References