Multiaxial Temperature- and Time-Dependent Failure Model

This model should be applicable to a variety of materials.

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A temperature- and time-dependent mathematical model predicts the conditions for failure of a material subjected to multiaxial stress. The model was initially applied to a filled epoxy below its glass-transition temperature, and is expected to be applicable to other materials, at least below their glass-transition temperatures. The model is justified simply by the fact that it closely approximates the experimentally observed failure behavior of this material: The multiaxiality of the model has been confirmed (see figure) and the model has been shown to be applicable at temperatures from −20 to 115 °C (−29 to 46 °F) and to predict tensile failures of constant-load and constant-load-rate specimens with failure times ranging from minutes to months.

The model is embodied in the following equation for the failure condition:

\[ AP^2 f_2 + B P h = 1 \]

where

- \( A \) and \( B \) are parameters that define the shape of an ellipsoidal failure surface in multiaxial stress space;
- \( P \) is a scaling factor that accounts for the temperature and time dependencies of the material;
- \( f_2 \) is the second deviatoric stress invariant, given by

\[ \sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11}\sigma_{22} - \sigma_{11}\sigma_{33} - \sigma_{22}\sigma_{33} + 3(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2) \]

- \( f_1 \) is the first stress invariant, given by \( \sigma_{11} + \sigma_{22} + \sigma_{33} \);
- the numerical subscripts denote Cartesian coordinate axes; and
- \( \sigma_j \) denotes the stress.

In the special case of constant \( P \), this model is equivalent to a modified Drucker-Pager model, and to the Tsai-Wu failure model that is traditionally used in evaluating composite materials.

The model is calibrated by use of data from tensile- and shear failure experiments. Data from tensile-adhesion and shear-adhesion failure tests of the material to which the model was initially applied show that the ratio between shear and tensile failure loads has a value of \( \approx 0.8 \), independent of time and temperature. This constant ratio, in combination with one sensor data point, can be used to calculate the values of \( A \) (1.0 for this material) and \( B \) (0.31754 for this material).

The value of the scale factor \( P \) is simply whatever value is needed to make a given failure surface pass through a known failure point for a given temperature and failure time. Hence, for example, once \( A \) and \( B \) are known, \( P \) as a function of time and temperature can be determined simply by solving the basic model equation for \( P \) and then inserting stress values from tensile or shear tests that involve known failure times and temperatures.

This work was done by Clyde F. Parrish of Kennedy Space Center.

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Technology Programs and Commercialization Office, Kennedy Space Center, (321) 867-8130. Refer to KSC-12236.

Experimental and Predicted Failure Points are plotted here for “napkin-ring” specimens of a filled epoxy that were loaded with both normal and shear stresses at a temperature of 70 °F (21 °C).

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