NONLINEAR FINITE ELEMENT ANALYSES OF REENTRY VEHICLE GRAPHITE NOSETIPS

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Introduction

Reentry vehicle graphite nosetips must be designed to withstand the extreme aerodynamic heating, pressure, and shape change associated with reentry environments. Expense and difficulty in obtaining sufficient instrumented flight test data, combined with requirements for increasing vehicle probability of survival, dictates the need for accurate material characterization and test proven analytical methods. The development of such analytical methods, however, is complicated by the unusual behavior of graphite under load and limited availability of multiaxial mechanical property data.

Molded graphite, a transversely isotropic material, exhibits different nonlinear stress-strain behavior in tension and compression and its strain response tends to be greater in biaxial tension than uniaxial tension ("biaxial softening" phenomenon, Ref. 1). Also, the material's inelastic strain behavior is not isovolumetric ("plastic" volume change) which indicates that classical theories of plasticity are not applicable.

A finite element analysis method which incorporates an appropriate nonlinear anisotropic stress-strain law has been developed (Ref. 2). The method, in conjunction with a physically based statistical failure theory (Ref. 3, 4), was applied to the prediction of thermostructural failure of graphite nosetips tested in a rocket nozzle environment. The method closely correlated with test results and provided evidence of the importance of accounting for inelastic volume change in the nonlinear stress-strain model.

Analytical Method

The nonlinear analysis method is an iterative solution technique which independently varies the material properties for each subsequent solution cycle based on the magnitude (nonlinearity) and sense (tension or compression) of the previous solution cycle's stress state. The method uses a temperature dependent material model developed by Jones and Nelson (Ref. 2). The strain energy

$$U = (\sigma_r \epsilon_r + \sigma_z \epsilon_z + \sigma_\theta \epsilon_\theta + \tau_{rz} \gamma_{rz})/2$$

is used to scale the degree of nonlinear response by relating material properties to multiaxial stress strains in accordance with the following empirical material property equation,

$$\text{Material Property} = A[1-B(U/U_o)^C]$$

where A, B, and C are constants determined from uniaxial stress-strain and strain-strain test data. The model accommodates unequal tension and compression nonlinear stress-strain curves of varying shape and variable Poisson's ratios. Use of the method implies that volume change can occur as a result of material tearing and microcracking ("biaxial softening").

The probability of failure theory (Refs. 3, 4) uses a stressed based, anisotropic, weakest link statistical approach. The method correlates well with uniaxial and biaxial experimental failure data.

Test and Analysis Correlations

Eight (8) graphite plug nosetips were tested in a shrouded rocket nozzle environment (Ref. 5). The specimen failure times were determined by ultrasonic measurements. Experimental probability of failure for this test series was 75 percent (six (6) specimens failed).

The new material model and associated iterative solution logic were updated into the SAAS III computer program (Ref. 6) and used to analyze the tested nosetip. Fig. 1 shows the test results and analysis predictions illustrating the excellent correlation obtained. One specimen failed without sonic detection. The upper and lower estimates of the test scatter (Fig. 1) were obtained by assuming that this specimen could have failed at any time up to and including 10.6 seconds, when it was first detected (by camera) to have failed.

To further evaluate the nonlinear analysis method, SAAS III linear solutions were completed. The stresses were substantially greater than those computed by the nonlinear method. The strains, however, were relatively insensitive to the method of analysis, as illustrated in Fig. 2. The linear strains were transformed into approximated nonlinear stresses, using a modified version of the Jones and Nelson model (Ref. 7). Fig. 1 also compares the linear analysis predicted failure curve with the test data. The results were somewhat conservative (consistent with other ground test analyses). The nonlinear results clearly removed the linear analysis conservatism.

Conclusions

Nonlinear analyses showed excellent agreement with test results. The Jones/Nelson nonlinear material model represents a reasonable approach to more accurately model the stress-strain behavior of graphite. The demonstrated availability of numerical techniques which accurately simulate the actual response of graphite represents a significant advance in thermostructural technology.

References

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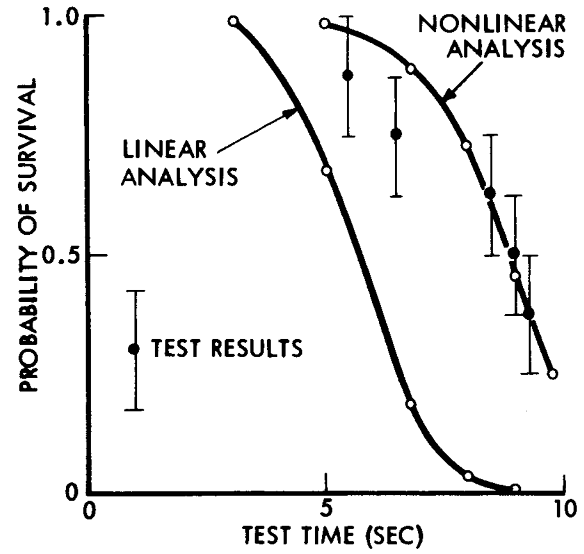

Figure 1. Probabilities of Survival Versus Test Time

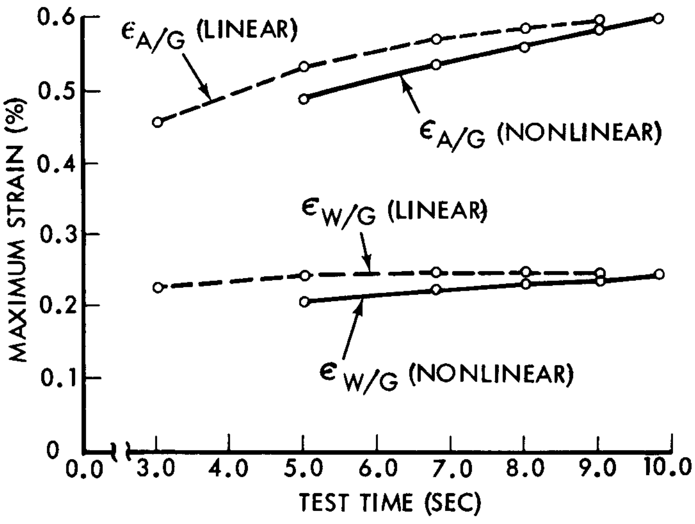

Figure 2. Maximum Across Grain and With Grain Strains Versus Test Time