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A STATISTICAL MODEL OF CARBON/CARBON COMPOSITE FAILURE

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The availability of modern filamentary composite materials for engineering design have provided tremendous opportunities for greatly improved performance. The most frequently cited advantage over conventional metallic materials is their high specific strength and stiffness. Unidirectional strengths of graphite/epoxy composites typically exceed those of high-strength steels with similar stiffness at only one-fifth of the weight. Other potential advantages over metals are corrosion resistance, radar transparency, and improved fatigue performance. One of the primary problems with using composites is that there is still little experience with these materials when compared with metals. This problem is compounded by the fact that the response of composites and their failure mechanisms are much more complex that those of metals.

Failure in filamentary composite materials involves a complex damage accumulation process. The material has randomly dispersed initial flaws in all phases: the fiber, the matrix, and the fiber/matrix interface. As load is applied the flaws grow and coalesce until some critical damage state is formed which results in failure. Most popular failure theories [2] frequently depend upon some anisotropic, distortional energy formulation. This type of approach is very useful in predicting yielding in metals but is not consistent with the mechanisms of failure in composites -- they do not yield in the same sense as metals! Of course, reasonable results can be obtained if the parameters of the model are adjusted based upon experimental data, but these approaches give very little insight into the failure mechanisms and are even less useful in understanding the statistical properties of the strength results. A failure model which considers the stochastic nature of the damage accumulation process is essential to assess reliability and to accurately scale the results from standard test specimens to composite structures.

A superior filamentary composite for high temperature applications is composed of carbon fibers in a carbon matrix. Carbon/carbon composites are the strongest known materials at very high temperatures. Three-dimensionally woven carbon/carbon composites have been used in nozzle components in several tactical missile systems because they exhibit lower erosion than carbon/phenolic composites. Carbon/carbon was also considered for the Advanced Solid Rocket Motor (ASRM) for the Space Shuttle. Among the reasons for not selecting this technological advance was that the carbon/carbon ITE was considered to be a structural component which was required to demonstrate a safety factor of 1.4 for a man-rated system. Available strength data and analysis techniques were inadequate to demonstrate this factor. The fact that the carbon/carbon ASRM ITE would have been much larger than any currently used carbon/carbon nozzle component raised additional concerns. More data on carbon/carbon strength and improved analysis techniques are required to properly analyze these designs.

Possibly the best source of data for carbon/carbon strength in circularly woven parts is from the qualification test rings from billets for the first stage of the Navy D-5 missile program manufactured by Textron Specialty Materials. Two tensile test rings were machined from one end of each billet and pressurized internally to determine the hoop strength of the composite. The magnitude of the strengths of these rings varied over a wide range of values. The rings which passed the qualification test were sent to NASA/MSFC in order to study the failure modes in an attempt to gain a better understanding of the scatter in the data. The first step in the analysis was to determine the effect of defects on the strength of the rings. Photographs were taken of both sides of the damaged region in all tensile rings. X-ray and CT scan investigations were also conducted on some of the rings to determine the utility of these methods in assessing significant defects. There was some correlation between strength and defects which could be reasonably easily detected using available methods, but most of the data scatter could not be explained by the presence of observable flaws.

Since there appears to be a significant randomness in carbon/carbon material strength which cannot be controlled or detected with current technology, a better model of the material failure based upon statistical principles should be employed. Such a model was developed. Simple applications of the model based upon the limited available data provide encouraging results that indicate that better design of test specimens would provide a substantially higher prediction for the design (A-basis) strength of carbon/carbon composites. Future test programs should consider size effects and defects caused by machining.

An A-basis strength for the carbon/carbon tensile rings from the first stage D-5 billets has been estimated. A statistical failure model has been developed for these rings which indicates that this strength may be very conservative for larger carbon/carbon parts. The results of these qualification tests still don't address the fundamental problem of failure in rocket nozzle components since they don't match the actual loading conditions. A better analysis technique which begins with the statistical distribution of fundamental constituent material properties would produce the ability to compare "apples to apples." A possible framework for improving the analysis would be a heterogeneous/non-continuum finite element approach on the mini-mechanical level similar to that used by Slattery and Hackett [1] on the micromechanical level.

PLEASE NOTE: Information on carbon/carbon composite materials is considered to be sensitive technology subject to export restrictions. This report was reviewed by the Research and Technology office at MSFC to preclude the release of sensitive information. A complete report was given to MSFC colleagues.

REFERENCES

1. Slattery, K.T. and R.M. Hackett, "Computational Simulation of the Creep-Rupture Process in Filamentary Composite Materials," Journal of Reinforced Plastics and Composites, 10-2 (1991) 184-197.

2. Soni, S.R., "A New Look at Commonly Used Failure Theories in Composite Laminates," AIAA, 1983, 171-179.