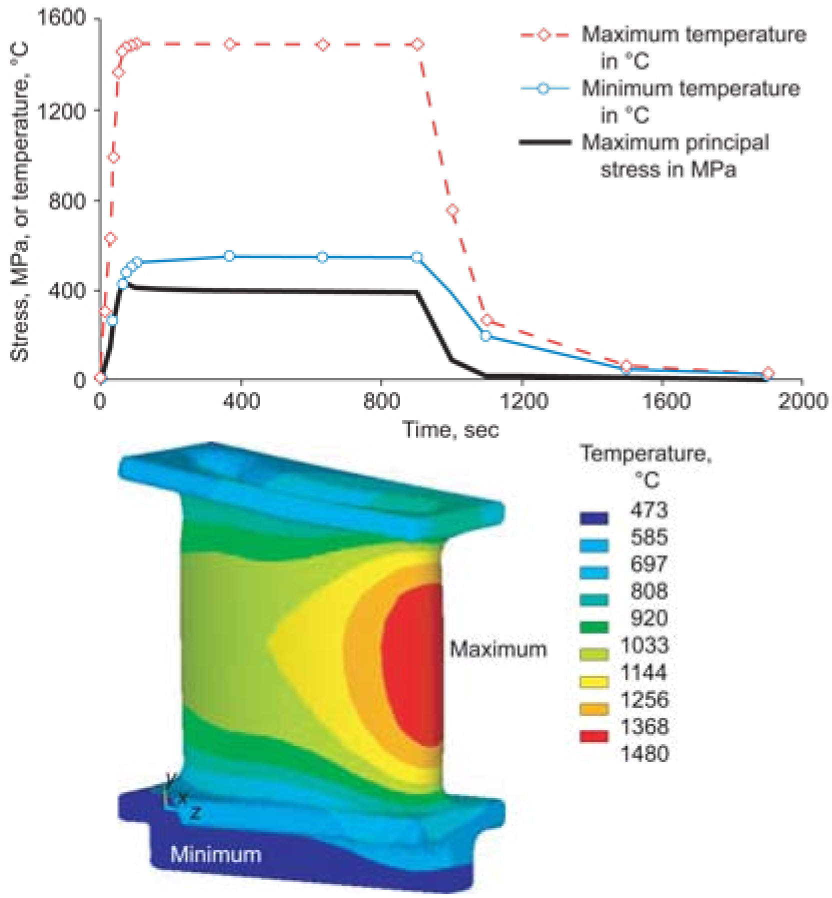
Life Predicted in a Probabilistic Design Space for Brittle Materials With Transient Loads

Analytical techniques have progressively become more sophisticated, and now we can consider the probabilistic nature of the entire space of random input variables on the lifetime reliability of brittle structures. This was demonstrated with NASA's CARES/*Life* (Ceramic Analysis and Reliability Evaluation of Structures/*Life*) code combined with the commercially available ANSYS/Probabilistic Design System (ANSYS/PDS), a probabilistic analysis tool that is an integral part of the ANSYS finite-element analysis program. ANSYS/PDS allows probabilistic loads, component geometry, and material properties to be considered in the finite-element analysis. CARES/*Life* predicts the time-dependent probability of failure of brittle material structures under generalized thermomechanical loading--such as that found in a turbine engine hot-section. Glenn researchers coupled ANSYS/PDS with CARES/*Life* to assess the effects of the stochastic variables of component geometry, loading, and material properties on the predicted life of the component for fully transient thermomechanical loading and cyclic loading.

In this implementation, the material parameters associated with reliability analysis--the Weibull and fatigue parameters--can themselves be made stochastic. This simulates batch-to-batch variations in the material reliability response or, alternately, the statistical uncertainty of the estimated parameters from the true parameters derived from experimental rupture data. It enables a more realistic assessment of brittle material component integrity. This capability will be useful in the design of ceramic turbine blades and vanes, thermal protection system parts, dental prosthetics, solid oxide fuel cells, and microelectromechanical systems (MEMS), as well as other applications that employ brittle materials.

A simplified turbine vane model simulating engine startup and shutdown follows, with details given in reference 1. The stator vane was assumed to be composed of a typical silicon nitride. The effects of a probabilistic engine startup/shutdown load profile and of probabilistic Weibull and fatigue parameters on the predicted integrity for a given number of startup/shutdown engine cycles were examined.

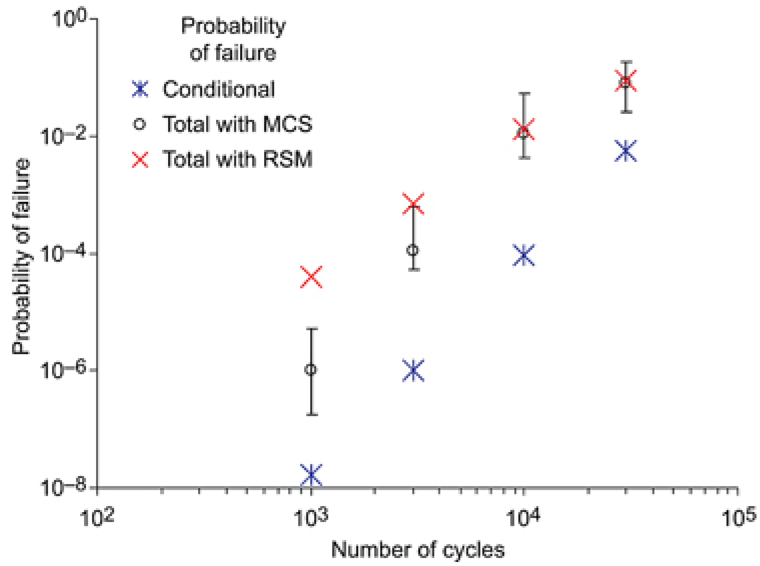
For the probabilistic analysis, 11 input parameters were identified as random quantities and were assigned a statistical distribution function to quantify their randomness. The random input variables impacting the finite-element analysis included material properties, thermal boundary conditions, and the startup time of the load cycle. The heat-transfer coefficient was assumed to be a coupled random value dependent on the variability of the heat-transfer mechanism coupled with the randomness of the mass flow. The random input variables affecting only the CARES/*Life* part of the analysis included the brittle material Weibull and fatigue parameters. The distribution types as well as the distribution parameters, although not based on measured data, nevertheless represented very realistic values.



Left: Maximum temperatures and stresses versus time for a simulated startup/shutdown cycle of a ceramic turbine vane. Right: Finite-element model results showing the stator vane temperature profile at 75 sec—the moment of highest loading. Maximum and minimum temperatures, 1480 and 473 °C; time step, 75 sec..

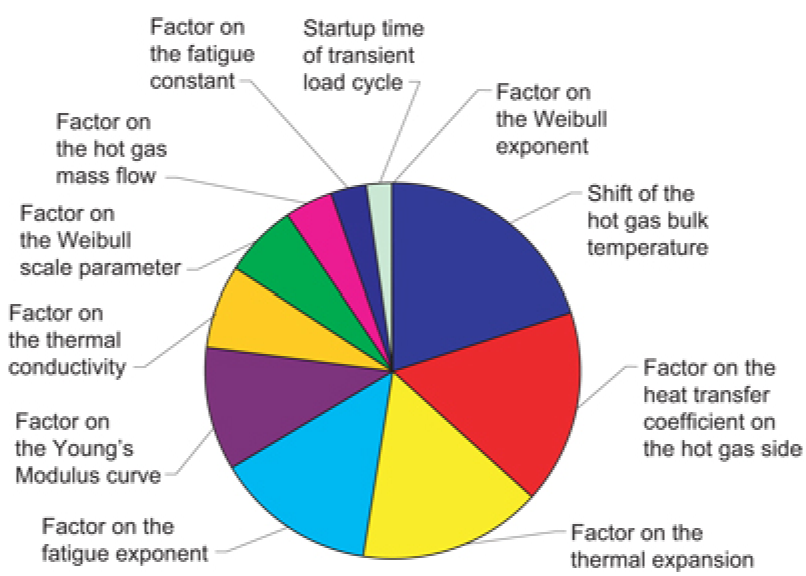
The transient operation was characterized by four phases. Phase 1, startup, lasted 50 sec. This was followed by phase 2--850 sec of hold time. Phase 3 was a 200-sec shutdown, and phase 4 was an 800-sec hold time for cooling down. The left figure illustrates this transient profile for one loading cycle. The right figure shows the stator vane thermal profile at 75 sec--the moment of maximum transient loading.

The following graph shows the average predicted failure probability (the socalled total probability) versus loading cycles for two probability methods--the Monte-Carlo simulation and the response-surface method--as well as a conditional (deterministic) finite-element analysis using averaged properties. This “total probability” is just the average of all the individual simulation trials. The differences between the deterministic and probabilistic analyses were due to highly nonlinear and skewed probability distributions. These results show that not taking stochastic response into account can lead to a nonconservative design. Correlation between the Monte-Carlo simulation and the response-surface method would improve as the number of simulations increased. In this case, we used 400 simulations for the Monte-Carlo simulation.



Results for conditional (deterministic) and total probability from the PDS using Monte-Carlo simulation (MCS) and the response-surface method (RSM).

The pie chart shows the sensitivity analysis results reported by ANSYS/PDS. Most of the input variables that significantly impact the failure probability either influence the temperature results or the stresses of the finite-element analysis. All of these input variables have a strongly nonlinear influence on the conditional failure probability.



Sensitivity of conditional failure probability at 1000 load cycles with Monte-Carlo simulation.

Long description of figure 4. Pie chart showing sensitivity factors on fatigue exponent, Young's modulus curve, thermal conductivity, Weibull scale parameter, hot gas mass flow, fatigue constant, transient load cycle, Weibull exponent, shift of hot gas bulk temperature, heat transfer coefficient on the hot gas side, and thermal expansion.

The significant difference between the conditional failure probability and the total failure probability indicates that ignoring the random influences outlined previously may lead to a nonconservative design. The conditional failure probability itself may be acceptably low, but the total failure probability could be, as in this example, two orders of magnitudes higher, which might not be considered safe enough.

We have demonstrated that a probabilistic life-prediction methodology for transient loading can be combined with a generalized probabilistic finite-element analysis program. This useful combination can be applied to other interesting problems, such as the effect of the reentry envelope on the reliability of certain passive ultra-high-temperature thermal protections systems or, for dental prosthetics, the effect on reliability of random loading direction and loading magnitude over time. It also would be useful in determining MEMS lifetime where tolerances on dimensions are a significant fraction of the overall part size.

Reference

1. Reh, Stefan; Palfi, Tamas; and Nemeth, Noel N.: Probabilistic Analysis Techniques Applied to Lifetime Reliability Estimation of Ceramics. Presented at the JANNAF 39th Combustion Subcommittee, 27th Airbreathing Propulsion, 21st Propulsion Systems Hazards Committee, and 3rd Modeling and Simulation Subcommittee Joint Meeting, Dec. 2003. Available from Chemical Propulsion Information Agency (CPIA).

Glenn contact: Noel N. Nemeth, 216-433-3215, Noel.N.Nemeth@nasa.gov
Authors: Noel N. Nemeth, Tamas Palfi, and Stefan Reh

Headquarters program office: Vehicle Systems
Programs/Projects: UEET