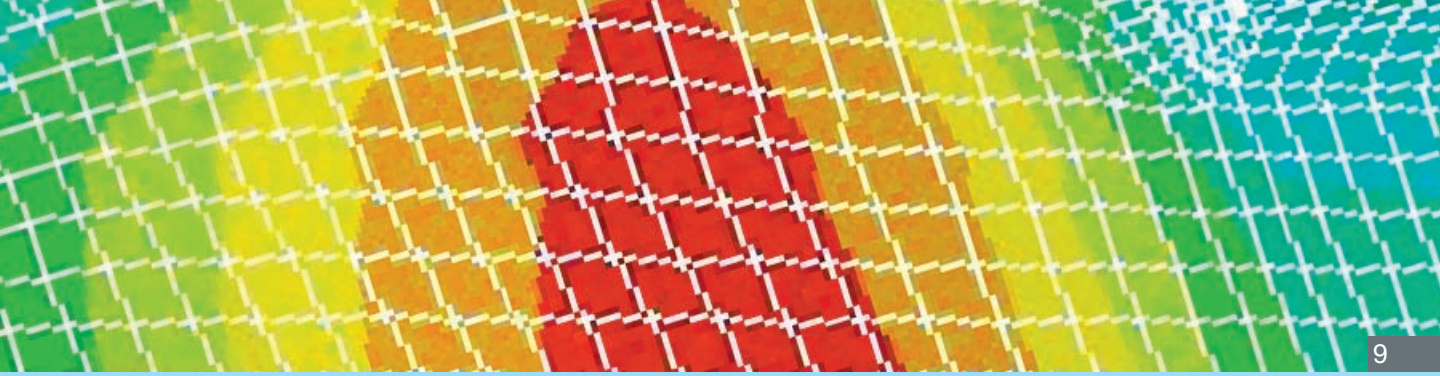

Designing Advanced Ceramic Parts That Last

Analysis is key in making sure these brittle components can withstand operational loads.

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Mention ceramics and many people immediately think of pottery or china. Indeed, the history of this material can be traced back over the past 10,000 years. Yet today's advanced ceramics bear little functional resemblance to their origins, and an expanding range of opportunities are opening up that take advantage of the robust mechanical, thermal and electrical properties of this unique material.

From a design engineer's perspective, advanced ceramics exhibit attractive high-strength properties at service temperatures that are well beyond use temperatures of conventional ductile materials. In advanced diesel and turbine engine applications, ceramic components have demonstrated functional abilities at temperatures above 1,300 degrees C, well beyond the operational limits of most conventional metal alloys.

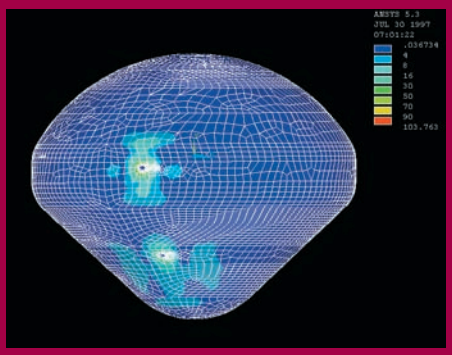
Ceramics have been used in the Mars microprobe aeroshell and rocket nozzles, for example. The material also has been used in hip and knee prosthetics, dental crowns and dental bridges, and industrial parts such as cutting tools, grinding wheels and bearings. In micro-electro-mechanical systems (MEMS), ceramics are used as microturbines, pressure sensors and thin film membranes. Oxygen ion-conducting ceramic membranes are being investigated for use in solid oxide fuel cells, oxygen separators and catalytic membrane reactors.

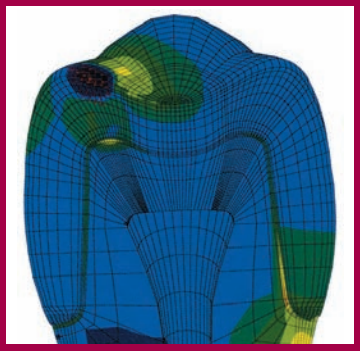
The interest of the military has been focused on missile radomes, advanced armor and blast protection systems for the armed forces' tactical wheeled-vehicle fleet. Advanced ceramics also are under consideration for use in body armor and advanced gun barrel systems.

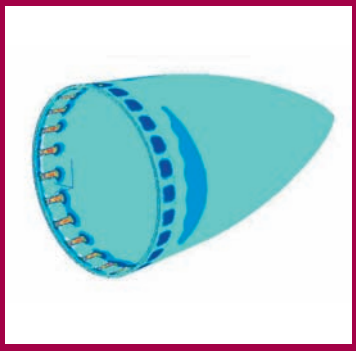
What Can Go Wrong?

Given all the positive implications associated with the use of advanced ceramics and their far-reaching impact, designing with this material is not straightforward and does have its drawbacks. Examples abound where swapping out metal components with ceramic components resulted in spectacular failures.

As with metal systems, ceramic engineering design requires consideration of materials properties







ANSYS was used in analyzing the Mars microprobe, a dental crown and a missile radome — items that were all made of advanced ceramics.

and operating environment. But the design penalty associated with ceramic materials is that they typically exhibit rather high tensile strength with a relatively low fracture toughness (typically quantified by KIC). This inherent undesirable combination must be considered when designing with ceramics. Lack of ductility (that is, lack of fracture toughness) leads to low strain tolerance and large variations in fracture strength.

The combination of high strength and low fracture toughness leads to relatively small critical defect sizes that cannot be detected by current non-destructive evaluation (NDE) methods. As a result, ceramic parts generally have a distribution of defects (characterized by various crack sizes and orientations), which leads to an observed scatter in component tensile strength. The distribution of defects leads to an apparent decrease in tensile strength as the size of the component increases. This is the so-called strength–size effect, where bigger components have an increased chance that more deleterious flaws are present. Design methods for ceramic components must account for this strength–size effect. This is accomplished by using system reliability concepts where the component is treated as a system, and the probability of system failure must be ascertained.

The WeibPar Algorithm

The probability of failure for a ceramic component can be determined by a Weibull analysis, which uses estimator functions to account for failure data and component geometry. (See sidebar.) Estimators should be consistent, efficient and reliable in producing unique, unbiased estimates of the distribution parameters. Different types of estimators include moment, least-squares and maximum likelihood. The WeibPar algorithm utilizes maximum likelihood estimators (MLE) because of their efficiency and the ease of handling complications, such as censored failure populations.

Many factors affect estimates of distribution parameters, especially the total number of test specimens. Initially, the uncertainty associated with parameter estimates decreases significantly as the number of test specimens increases. However, a point of diminishing returns is reached when the cost

Understanding Weibull Analysis

The inherent scatter in strength and size effects generally means that reliability analysis of advanced ceramic parts is usually more favorable than using standard safety factors. If a brittle material with an obvious scatter in tensile strength is selected for its high-strength attributes or inert behavior, then statistical analysis should be an integral part of the design process. But this statistical approach involves a certain risk of unacceptable performance, identified as a component's probability of failure (or alternatively, component reliability). The primary concern is minimizing this risk in an economical manner.

The typical approach to designing structural components with varying stress fields involves discretizing the component to characterize the stress field using finite element methods. Since ceramic component failure may initiate in any of the discrete elements (not just the most highly stressed region, or hot spot), it is convenient to consider a component as a system and utilize system reliability theories.

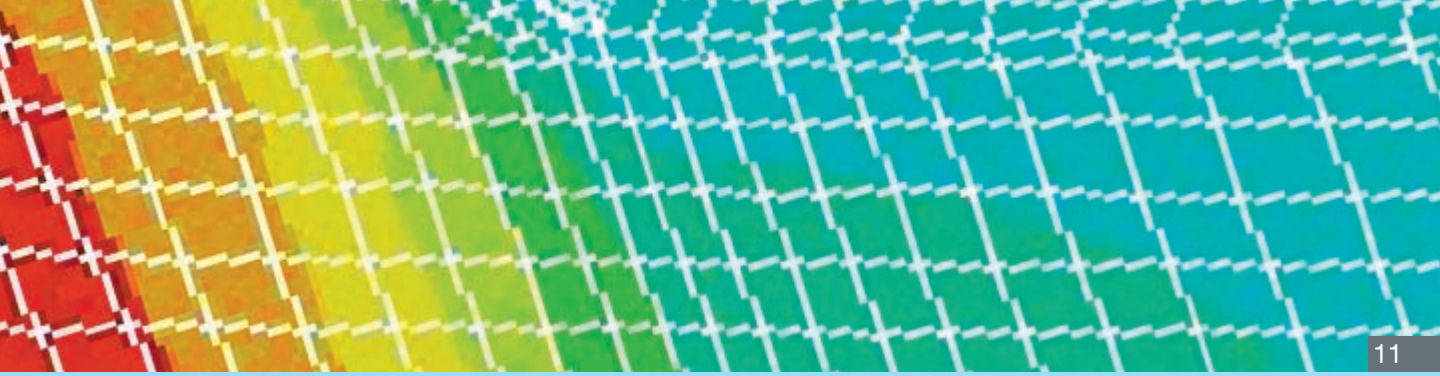
In this respect, a component behaves as a series system if it fails when one discrete element fails and can be modeled using weakest-link reliability theories. In contrast, with a parallel system component (when failure of a single element does not cause the part to fail), the remaining elements sustain load through redistribution. This type of failure can be modeled with what is referred to as bundle theories. Weakest-link theories and bundle theories represent the extremes of failure behavior modeled using reliability analysis. They suggest more complex systems such as *r out of n* systems, in which a component (system) of *n* elements functions if at least *r* elements have not failed.

The historical perspective has been to assume that the failure behavior of the brittle materials is sudden and catastrophic. This type of behavior fits within the description of a series system; thus a weakest-link reliability approach is adopted. This requires that the probability of failure of a discrete element must be related to the overall probability of failure of the component. This leads to an interaction of finite element software such as ANSYS and probabilistic design software such as CARES/Life and WeibPar.

If the failure of an individual element is considered a statistical event and if these events are independent, then the probability of failure of a discretized component that acts as a series system is given by the expression

$$P_f = 1 - \prod_{i=1}^{N} \left(1 - P_i\right)$$

where N would correspond to the number of finite elements in a given component analysis. Here P_i is the probability of failure of the ith discrete element. The next step involves adopting an expression for the probability of failure of the ith discrete element for a simplified state of stress — that is, a uniaxial tensile stress.



of performing additional strength tests may not be justified. This suggests that a practical number of strength tests should be performed to obtain a desired level of confidence associated with a parameter estimate. One should not simply adopt widely cited rules-of-thumb (for example, the "magic" number of 30). The requisite number of test specimens depends on the precision established for each design application.

Tensile and flexural specimens are the most commonly used test configurations for ceramic materials, and, as discussed previously, observed strength values depend on specimen size and geometry. Parameter estimates can be computed based on a given specimen geometry. However, the parameter estimates should be transformed and utilized in a component reliability analysis as material-specific parameters.

Advanced ceramics typically contain two or more active flaw distributions (for example, failures due to inclusions or machining damage), and each will have its own strength distribution parameters. The censoring techniques available in the WeibPar algorithm for the two-parameter Weibull distribution require positive confirmation of multiple flaw distributions, which means fractographic examination must be done to characterize the fracture origin in each specimen.

Working with CARES/Life

The CARES/Life algorithm (originally developed at NASA Glenn Research Center) has enjoyed a highly successful interaction with ANSYS software for years. Relative to ceramic component design, heat transfer and linear-elastic analysis are typically utilized to determine the temperature field and stress field using ANSYS. The component reliability analysis module in CARES/Life uses the thermoelastic results to calculate the reliability for each element utilizing a specified reliability model. Using meshing options available in ANSYS, each element can be made arbitrarily small, so the stress field in an element can be approximated as constant throughout a sub-element.

CARES/Life post-processes ANSYS results files, and it is compatible with a number of the 2-D, 3-D, axisymmetric and shell elements in the ANSYS suite

In the ceramic and glass industry, the Weibull distribution is universally accepted as the distribution of choice in representing the underlying probability distribution function for tensile strength. A two-parameter formulation and a three-parameter formulation are available for the Weibull distribution. However, the two-parameter formulation usually leads to a more conservative estimate for the component probability of failure. The two-parameter Weibull probability density function for a continuous random strength variable, denoted as Σ, is given by the expression

$$f_{\Sigma}(\sigma) = \left(\frac{\alpha}{\beta}\right)\left(\frac{\sigma}{\beta}\right)^{(\alpha-1)} exp\left[-\left(\frac{\sigma}{\beta}\right)^{\alpha}\right]$$

for $\sigma > 0$, and

$$f_{\Sigma}(\sigma) = 0$$

for $\sigma \leq 0$. Here α (a scatter parameter, or Weibull modulus) and β (a central location parameter, typically referred to as the Weibull scale parameter) are distribution parameters. In the ceramic literature, when the two-parameter Weibull formulation is adopted then m is used for the Weibull modulus α, and σ_0 or σ_θ is used for the Weibull central location parameter. A brief discussion regarding parameter estimation is presented under the subheading "The WeibPar Algorithm" in the main text of this article. However, a key point is that specimen-specific parameters must be transformed into material-specific parameters. Material-specific parameters are used in component analysis. A thorough description of established means for reporting Weibull distribution parameters can be found in the American Society for Testing and Materials (ASTM) standard C1239, as well as the International Standards Organization (ISO) standard designated as FDIS 20501. The product series given in the first equation takes the integral form

$$P_f = 1 - exp\left[-\int\left(\frac{\sigma}{\sigma_0}\right)^m dV\right]$$

in the limit as N approaches infinity. Weibull first proposed this integral representation for the probability of failure. The expression is integrated over all tensile regions of the specimen volume if the strength-controlling flaws are randomly distributed through the volume of the material, or over all tensile regions of the specimen area if flaws are restricted to the specimen surface. For failures due to surface defects, the probability of failure is given by a surface integral similar to the expression. This final equation and its companion surface integral serve as the starting point for reliability analysis conducted using the CARES/Life algorithm.

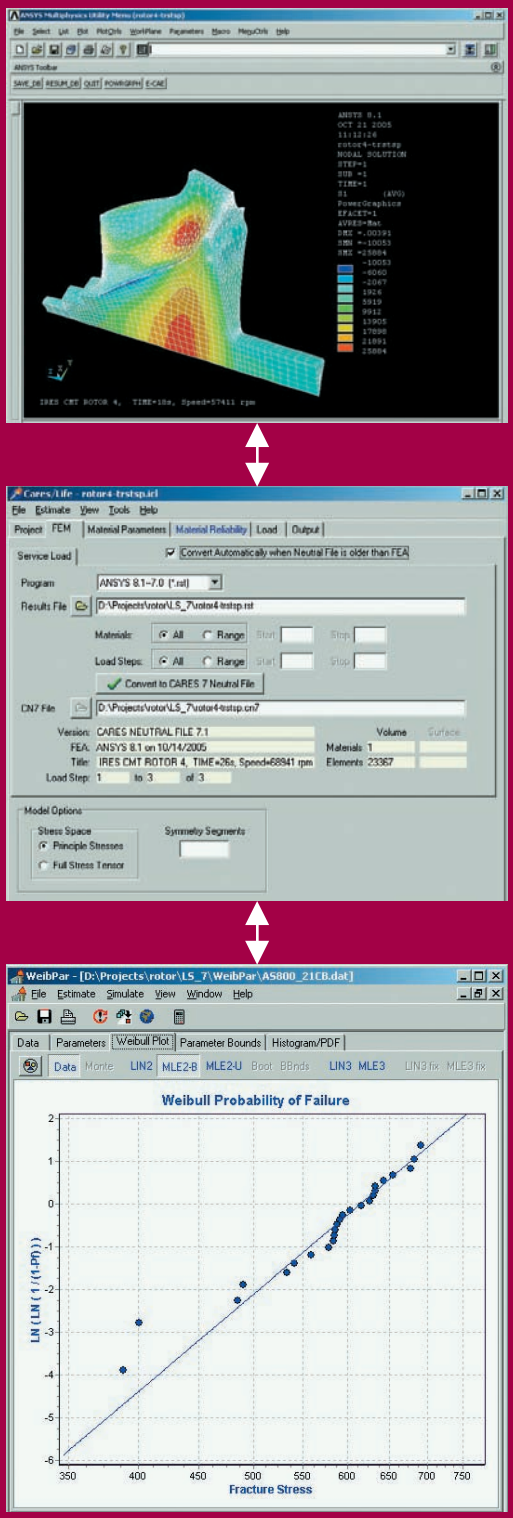
of elements. Reliability calculations are performed using stress values at the Gaussian integration points of the element. Using element integration points enables the element to be divided into sub-elements, in which integration point sub-volumes, sub-areas and sub-temperatures are calculated. The location of the Gaussian integration point in the finite element and the corresponding weight functions are adopted when the sub-element volume and/or area is calculated. The number of sub-elements in each element depends on the integration order chosen and the element type. If the probability of survival for each element is assumed to be mutually exclusive, the overall component reliability is the product of all the calculated element survival probabilities. (See the first equation in the sidebar.)

When subjected to elevated service temperatures, advanced ceramics can easily exhibit complex thermomechanical behavior that is both inherently time-dependent and hereditary in the sense that current behavior depends not only on current conditions but also on thermomechanical history. Keep in mind that the ability of a component to sustain load degrades over time, and it depends on a variety of effects such as oxidation, creep, stress corrosion and cyclic fatigue. Stress corrosion and cyclic fatigue result in a phenomenon called subcritical crack growth (SCG). This failure mechanism initiates at a pre-existing flaw and continues until a critical length is attained. At that point, the crack grows in an unstable fashion, leading to catastrophic failure. The SCG failure mechanism is a time-dependent, load-induced phenomenon. A reliability model for this mechanism is available in the CARES/Life algorithm.

Summary

The ability to analyze complex component geometries along with related boundary conditions has led to numerous technological breakthroughs over the past quarter century. Moreover, when commercial codes such as ANSYS are combined with specialty algorithms such as CARES/Life and WeibPar, the resulting computational architecture provides the engineer powerful predictive tools for these types of focused applications. The ability to study numerous design options can lead to productivity gains and innovation because a near-optimized design can be evaluated before a prototype component is fabricated. ■

Further information on CARES and WeibPar software can be found at www.ceramicreliability.com.



In analysis of parts such as this ceramic rotor, the CARES/Life algorithm predicts component reliability based on input from ANSYS software and the WeibPar algorithm.