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# QUANTIFICATION OF THRMAL-STRUCTURAL UNCERTAINTIES IN ENGINE COMBUSTOR COMPOSITE LINERS

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## ABSTRACT

A typical hot structural component within an engine such as composite combustor liner is computationally simulated and probabilistically evaluated in view of the numerous uncertainties associated with the structural, material, and thermo-mechanical load variables (primitive variables) that describe the combustor. The combustor is evaluated for local stresses. Results show that the scatter in the combined stress near the support is significantly dependent upon the uncertainties in the through thickness thermal gradients, the liner material thickness, the coefficient of thermal expansion, and the axial and both the axial and shear moduli.

## INTRODUCTION

Aerospace propulsion systems are a complex assemblage of structural components that are subjected to a variety of thermal and mechanical loading conditions. Inherent variability of material properties and fabrication processes, as well as geometrical tolerances introduce additional uncertainties. Deterministic structural analysis methods are not adequate to properly evaluate the design parameters variability. Furthermore, these methods could lead to non-conservative designs since safety factors do not quantify the probability of failure.

As an alternative to the deterministic approach, Probabilistic Structural Analysis Methods (PSAM) are being developed at NASA Lewis Research Center (ref. 1) which enables the assessment of the fluctuating load effects, variable material properties, and uncertain geometries on the scatter of structural responses (eigenvalues, frequencies, effective stresses, etc...). PSAM also provides a systematic way to quantify sensitivities associated with the corresponding uncertainties in the design variables to the system model. PSAM is embedded in a computer code NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) (refs. 2 and 3).

In the recent past, NESSUS has been used (ref. 4) to computationally simulate and probabilistically evaluate a typical hot structural component within an engine such as composite combustor liner. The probabilistic analysis results showed that the scatter in the combined stress is not uniform along the length of the combustor. Furthermore, the coefficient of thermal expansion, the hoop modulus of the liner material, and the thermal load profile dominate stresses near the support and the mid-span of the combustor liner. The objective of this paper is to further probabilistically evaluate the effects of the uncertainties of through thickness thermal load gradients for a typical ceramic matrix combustor liner. The combustor liner is separately evaluated for local stresses using low, high and mixed low/high moduli ceramic matrix composite (CMC) combustor. Furthermore, this paper determines the uncertainties associated with the dominant parameters for reliable/robust combustor liner design. Due to the fact this is a finite element based simulation where the physics are properly represented, the authors expect that the experimental data for these responses will verify or nearly so to their respective predicted distributions.

## FUNDAMENTAL APPROACH AND CONSIDERATIONS

One of the major problems encountered in the analysis of the hot section components in an engine, such as a combustor liner is that it has to be economically viable inclusive of life-cycle costs and reliability as well as environmentally acceptable. Furthermore, high temperature ceramic matrix composites that might be used should possess material characteristics to provide long term durability as well as resistance to possible through thickness high thermal gradients. In addition, the recommended ceramic matrix composite materials should have properly connected economical fabrication processes to minimize overall manufacturing costs. The presently available methods/programs do not allow us easily to statistically

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quantify the uncertainties in the above described design parameters. Therefore, using the NESSUS code, dominant parameters can be identified to achieve acceptable vibration frequency values, buckling loads, and combined stress values..

## FINITE ELEMENT MODEL

A three dimensional preliminary configuration of a typical hot section component such as combustor liner is computationally simulated by using bilinear isoparametric variable-thickness shell element based on Reissner-Mindlin plate and shell theories (see Fig. 1). The element is a four-noded quadrilateral in three dimensional space. Initially, the liner is composed of a typical low modulus ceramic matrix composite material (SiC/SiC). In the subsequent analysis the liner is composed of high modulus ceramic matrix composite material (SiC/SiC). For the final analysis, the low modulus composite material is used only in the vicinity of the left hand side support, whereas for the remaining length of the liner, high modulus is used. As shown in Fig. 1, the combustor liner is exposed to uniform pressure loading and variable thermal loading. In addition through liner thickness thermal gradient is also considered during the analysis. In the initial finite element analysis it was assumed that all the nodes at the support locations were allowed to freely expand both in radial and circumferential directions. However, all other nodes along its length were assumed to rotate freely and displace in all directions.

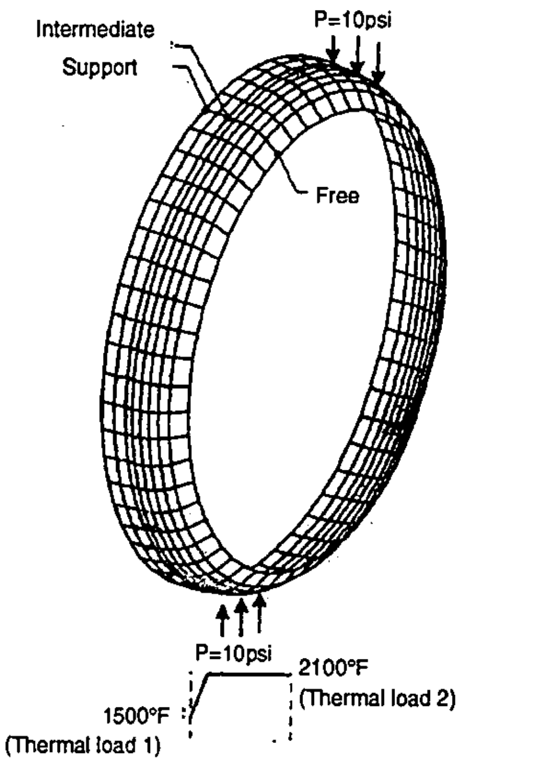


**Figure 1. Typical Combustor Liners for Wide Body Commercial Jet Engines.**

## PROBABILISTIC MODEL

The following primitive variables were considered in the probabilistic analysis:

(1) Density of the liner material
(2) Coefficient of thermal expansion
(3) Thickness of the liner
(4) Pressure load
(5) Through thickness thermal loading at the support
(6) Through thickness thermal loading along the length of the combustor
(7) Flexible support conditions
(8) Material properties

In the case of the material properties, the axial modulus, the hoop modulus, three directional shear moduli, and Poisson's contribution were considered for the analyses. In the present probabilistic analysis these material property variables were assumed to be independent of each other. The normal distribution is assumed to represent the uncertainties in the above discussed primitive variables. Normal distribution assumption is justified because all those properties vary equally on either side of the assumed mean values. Furthermore, a 100 F through thickness thermal gradient was assumed every where and these thermal loads were also assumed to vary according to normal distribution. NESSUS, however, has 10 (ten) different types of distributions. When the influence of distribution-type is considered important, sensitivity studies can be performed readily to assess their respective effects. Initially, the NESSUS/FEM (Finite Element Methods) module was used to analyze deterministically the combustor liner for mean values of these primitive variables. In the subsequent probabilistic analyses, each primitive variable is perturbed independently and by a different amount. Usually, the perturbed value of the primitive variable is obtained by a adding a certain factor of the standard deviation on either side of the mean value.

In general, the finite element equation for motion is written as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = F(t) \qquad (1)$$

(1) where [M], [C], and [K] denote the mass, damping, and stiffness matrices respectively. These matrices are calculated probabilistically in the NESSUS code. Furthermore, $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are the acceleration, velocity and displacement vectors at each node, respectively. The forcing function vector, F(t), is time independent at each node. In this paper, the static case is considered by setting the mass and damping matrices to zero and considering the forcing being independent of time in equation (1) such that

$$[K]\{u\} = F \qquad (2)$$

(2) Finally, the NESSUS/FPI (Fast Probability Integration) module extracts the combined stress values to calculate the probabilistic distribution function for the stress and respective sensitivities associated with the corresponding uncertainties in the primitive

variables. The mean, distribution type and percentage variation for each primitive variable is given in Tables I and II. For the details of the probabilistic simulations and solutions see (refs. 2 and 3).

| Primitive variables | Dist. type | Mean value | Scatter, ± percent |
|---|---|---|---|
| Density | Normal | 0.1002 lbs/in.-sec$^2$ | 5.0 |
| Coefficient of thermal expansion | | 1.75X10$^{-6}$in./in./°F | |
| Thickness | | 0.1in. | |
| Pressure load | | 10psi | |
| Thermal load ($T_1$) | | 1500°F | |
| Thermal load ($T_2$) | | 2100°F | |
| Axial modulus | | 30.72 msi | |
| Hoop modulus | | 31.62 msi | |
| Poisson's contribution | | 4.83 msi | |
| Shear modulus | | 12.99 msi | |
| Shear modulus | | 12.99 msi | |
| Shear modulus | | 13.62 msi | |

**Table 1 - Primitive Variables and Uncertainties for Probabilistic Structural Analysis of Low Modulus Ceramic Matrix Composite Combustor Liner (Random input data)**

| Primitive variables | Dist. type | Mean value | Scatter, ± percent |
|---|---|---|---|
| Density | Normal | 0.1002 lbs/in.-sec$^2$ | 5.0* |
| Coefficient of thermal expansion | | 1.75X10$^{-6}$in./in./°F | |
| Thickness | | 0.1in. | |
| Pressure load | | 10psi | |
| Thermal load ($T_1$) | | 1500°F | |
| Thermal load ($T_2$) | | 2100°F | |
| Axial modulus | | 37.98 msi | |
| Hoop modulus | | 38.93 msi | |
| Poisson's contribution | | 5.73msi | |
| Shear modulus | | 15.76 msi | |
| Shear modulus | | 15.76 msi | |
| Shear modulus | | 16.87 msi | |

*Assumed for computational convenience - different values are not expected to change the order of sensitivity factors, though their magnitudes may change slightly.

**Table 2 - Primitive Variables and Uncertainties for Probabilistic Structural Analysis of High Modulus Ceramic Matrix Composite Combustor Liner (Random input data)**

## DISCUSSION OF RESULTS

The combustor material has to satisfy all the structural reliability and safety requirements against the thermo-mechanical loadings. The combustor liner was initially analyzed to obtain the cumulative distribution functions (CDF) of the probabilistic buckling loads and vibration frequencies as well as corresponding sensitivity factors (ref. 4). In addition to satisfying the design requirements with allowable vibration frequencies as well as buckling loads, the stress level in the combustor liner should be below some critical value. Therefore, the probabilistic distribution of the combined stress response was initially calculated for low modulus ceramic matrix composite liner for thermo-mechanical loadings and considering both axial and through thickness thermal gradients (see Fig. 2). It is important to note that the support conditions were assumed to allow the unrestrained radial growth of the combustor. According to Fig. 3, through thickness thermal gradients, the thickness, the coefficient of thermal expansion, and the axial and shear moduli have considerable impact on combined stress with the through thickness thermal gradients having most significant impact. In the subsequent analysis, high modulus ceramic matrix composite material was used to calculate probabilistic combined stresses (see Fig. 4). However for this case, from the sensitivity factors from Figure 5, the scatter in the coefficient of thermal expansion has the highest impact on the probabilistic combined stresses followed by the through thickness thermal gradients, the liner thickness, and finally the axial and shear moduli of the composite. It is important to note that by decreasing the scatter of the thermal expansion coefficient one can increase the reliability of the combustor liner. Finally, in order to reduce the stiffness of the liner material near the support only, a liner with low modulus ceramic matrix composite was assumed near the support and high modulus ceramic matrix composite was used for the remaining length of the liner. This liner material was then analyzed for evaluating probabilistic combined stresses (see Fig. 6) and the respective factors were determined (see Fig. 7). It is important to note that for the mixed material liner the liner material thickness, through thickness thermal gradients, and the coefficient of thermal expansion have equally significant impact on probabilistic combined stresses. For all the above three cases, the magnitude of the mean combined stress near the support vary from 13 ksi to 15 ksi. In addition both the through thickness and axial thermal gradients were dominant contributors to stress magnitude near the support.

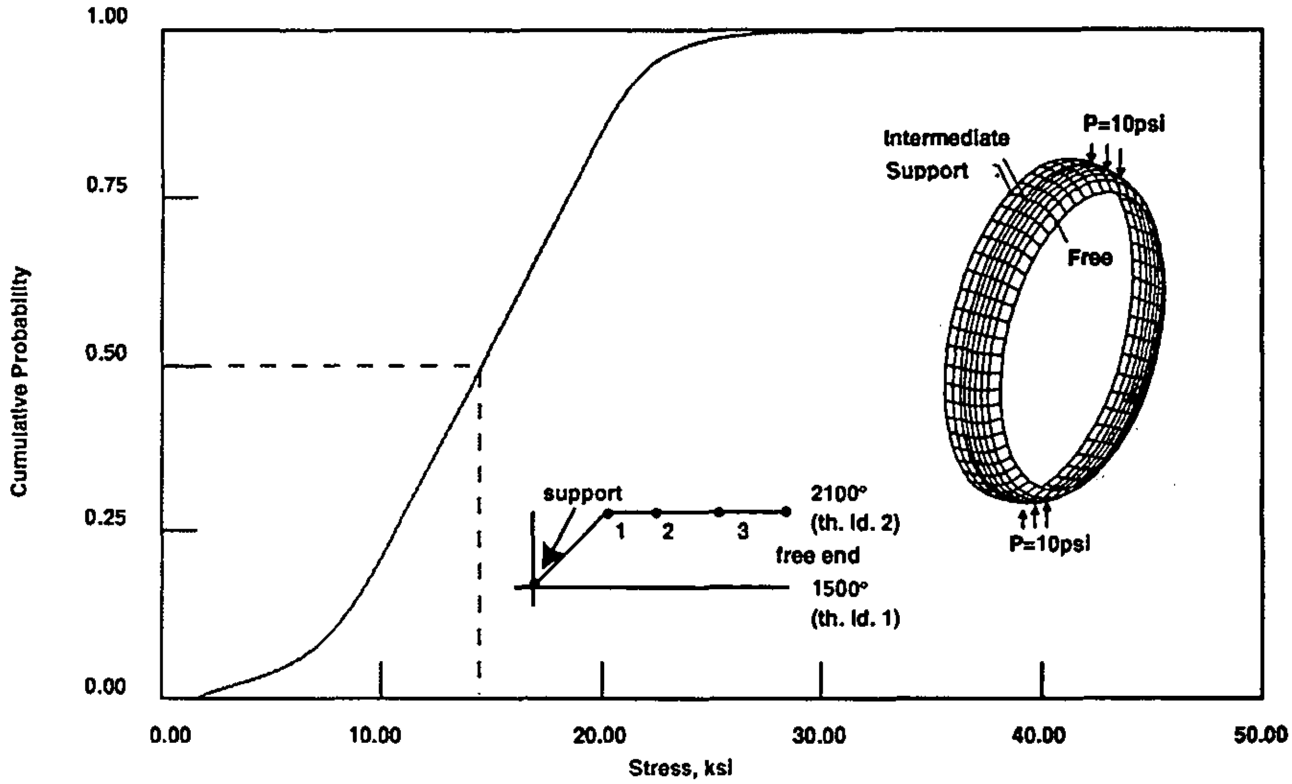


Figure 2. Probable Stress Range at the Unrestrained Support of Low Modulus CMC Combustor Liner

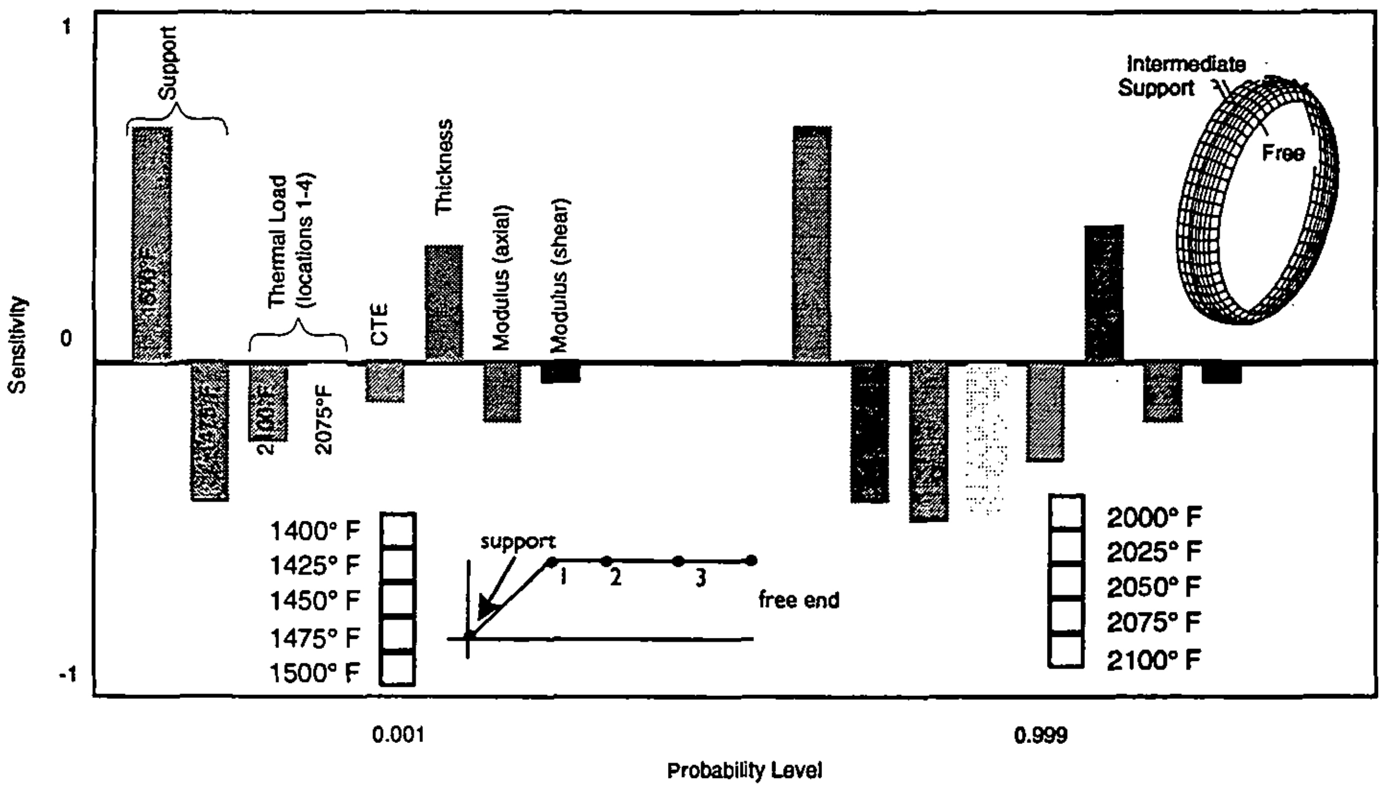


Figure 3. Temperature Gradients Dominate Stress at the Unrestrained Support for Low Modulus CMC Combustor Liner

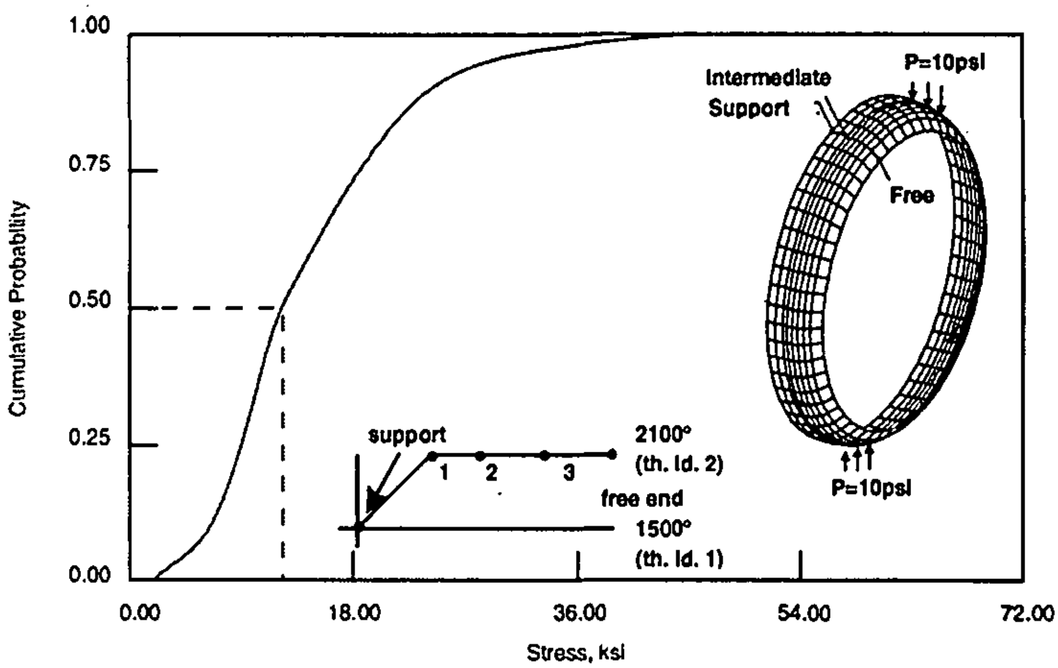


**Figure 4. Probable Stress Range at the Unrestrained Support for the High Modulus CMC Combustor Liner**

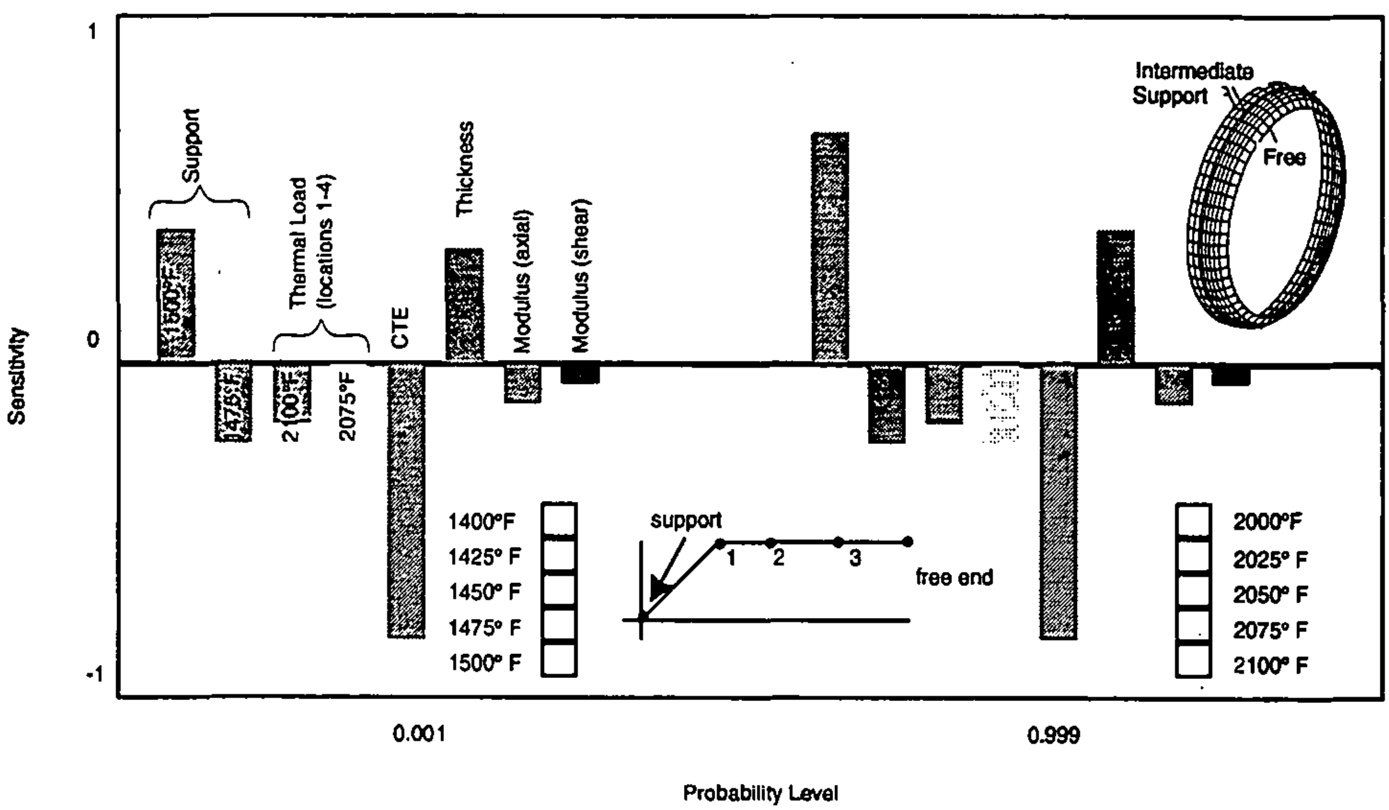


**Figure 5. CTE Dominates Stress at the Unrestrained Support for High Modulus CMC Combustor Liner**

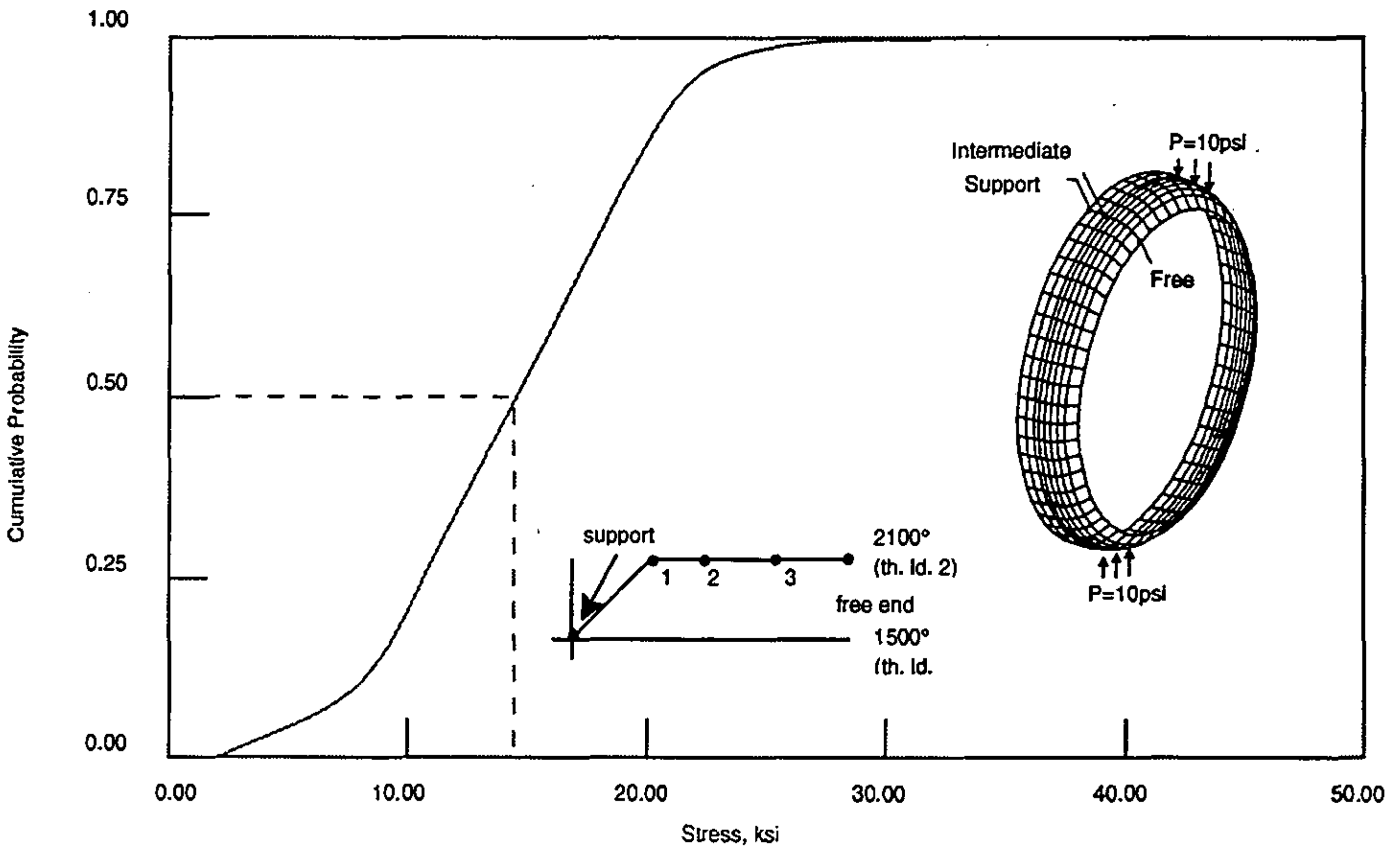


Figure 6. Probable Stress Range at the Unrestrained Support for the Mixed Low/High Modulus CMC Combustor Liner

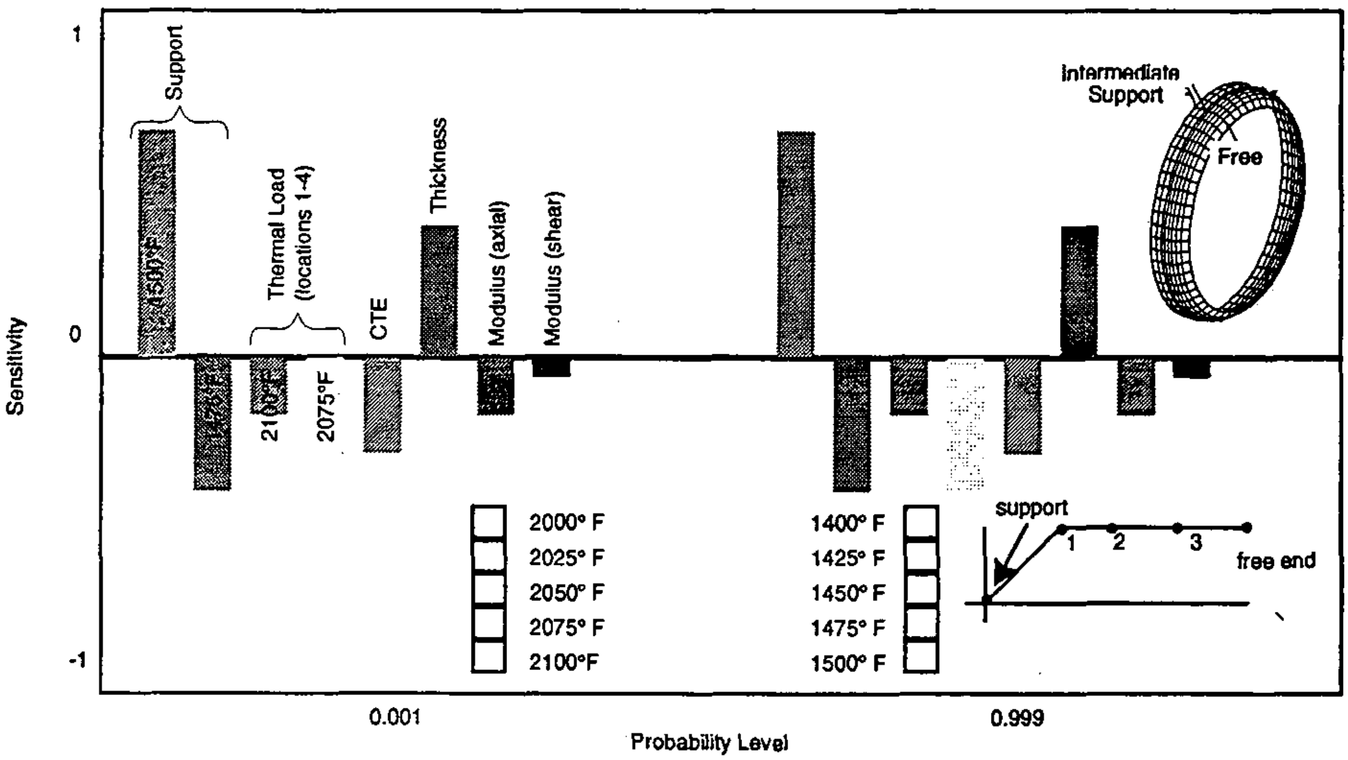


Figure 7. Temperature Gradients Dominate Stress at the Unrestrained Support for Mixed Low/High Modulus CMC Combustor Liner

## CONCLUSIONS

The computational simulation of probabilistic evaluation of a typical hot structural hot structural component within an engine such as ceramic composite combustor liner is demonstrated using the NESSUS computer code. The combustor is analyzed for compressive pressure loading and nonuniform thermal loading along its length, In addition through thickness thermal gradients were considered during the probabilistic anlyses. The cumulative distribution functions (CDF's) for combined stresses were evaluated using first low modulus ceramic matrix composite, followed by high modulus ceramic matrix composite, and finally with a combination of these two materials. The results indicate that: (1)the variations in both the through thickness and axial thermal gradients are dominant contributors to stress magnitude near the support; (2) the scatter in the liner thickness as well as the coefficient of thermal expansion contribute significantly to the stress magnitude (comparable to the through thickness thermal gradient); (3) fibers with different moduli affect magnide of mean stress near support. Collectively, the results provide quantifiable guidance on dominant parameters for reliable/robust combustor liner design and optimum support condition.

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