Probabilistic Assessment of a CMC Turbine Vane

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In order to demonstrate the advanced CMC technology under development with in the Ultra Efficient Engine Technology (UEET) program, it has been planned to fabricate, test and analyze an all CMC turbine vane made of the a SiC/SiC composite material. The objective was to utilize a 5-II Satin Weave SiC/CVI SiC/ and MI SiC matrix material that was developed in-house under the Enabling Propulsion Materials (EPM) program, to design and fabricate a stator vane that can endure successfully 1000 hours of engine service conditions operation. The design requirements for the vane are to be able to withstand a maximum of 2400 °F within the substrate and the hot surface temperature of 2700 °F with the aid of an in-house developed Environmental/Thermal Barrier Coating (EBC/TBC) system.. The vane will be tested in a High Pressure Burner Rig at NASA Glenn Research Center facility. This rig is capable of simulating the engine service environment.

The present paper focuses on a probabilistic assessment of the vane. The material stress/strain relationship shows a bilinear behavior with a distinct knee corresponding to what is often termed as first matrix cracking strength. This is a critical life limiting consideration for these materials. The vane is therefore designed such that the maximum stresses are within this limit so that the structure is never subjected to loads beyond the first matrix cracking strength. Any violation of this design requirement is considered as the failure. Probabilistic analysis is performed in order to determine the probability of failure based on this assumption. In the analysis, material properties, strength, and pressures are considered random variables. The variations in properties and strength are based on the actual experimental data generated in house. The mean values for the pressures on the upper surface and the lower surface are known but their distributions are unknown. In the present analysis the pressures are considered normally distributed with a nominal variation. Temperature profile on the vane is obtained by performing a CFD analysis and is assumed to be deterministic.

Results are presented in the form of cumulative probability distribution for the maximum stresses, failure probability and the sensitivity of the participant variables with their order of importance. The sensitivity information is helpful in improving design and reliability of the vane as it provides upfront information on quality control aspects.

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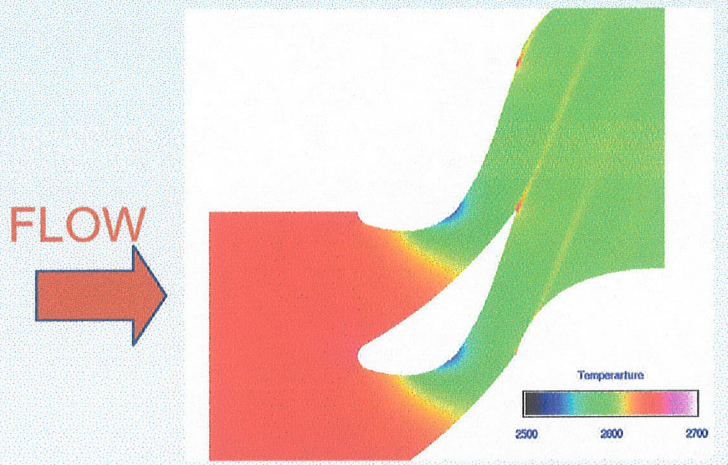
Presentation Outline

- Background
- Objectives
- Approach
- Probabilistic Analysis Theory
- Cases studied
- Stress response distributions and sensitivities
- Risk assessment
- Summary
- Future research plans

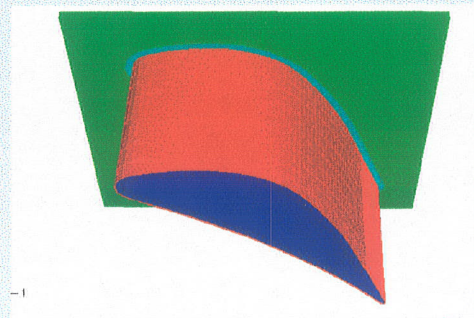
Background

- **UEET Goal: Design/Fabricate/Analyze/Test an all CMC turbine stator vane capable of withstanding 100 hours life in a simulated engine environment in High Pressure Burner Rig at NASA Glenn**
  - Successful demonstration reported earlier at the UEET annual conference
  - Performed deterministic thermal/stress analyses of vane and results reported earlier
- **Benefits: Allows higher combustor exit temperatures**
  - 2700 ^{0}F surface temperature capability goal
  - Potential cooling requirement reduction of 15-25%

CMC Turbine Vane Analysis

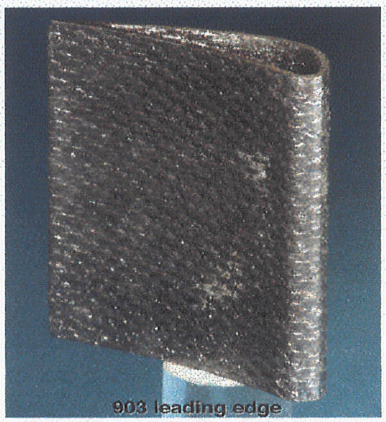


- **Goal**:
- Prediction of the temperature and stress conditions present in the mid-span of the vane.
- **Approach**:
- Flow boundary conditions modeled via CFD analysis.
- Attachment concept approximated.
- Vane without internal rib was modeled.



- CFD Analysis for HPBR Environment

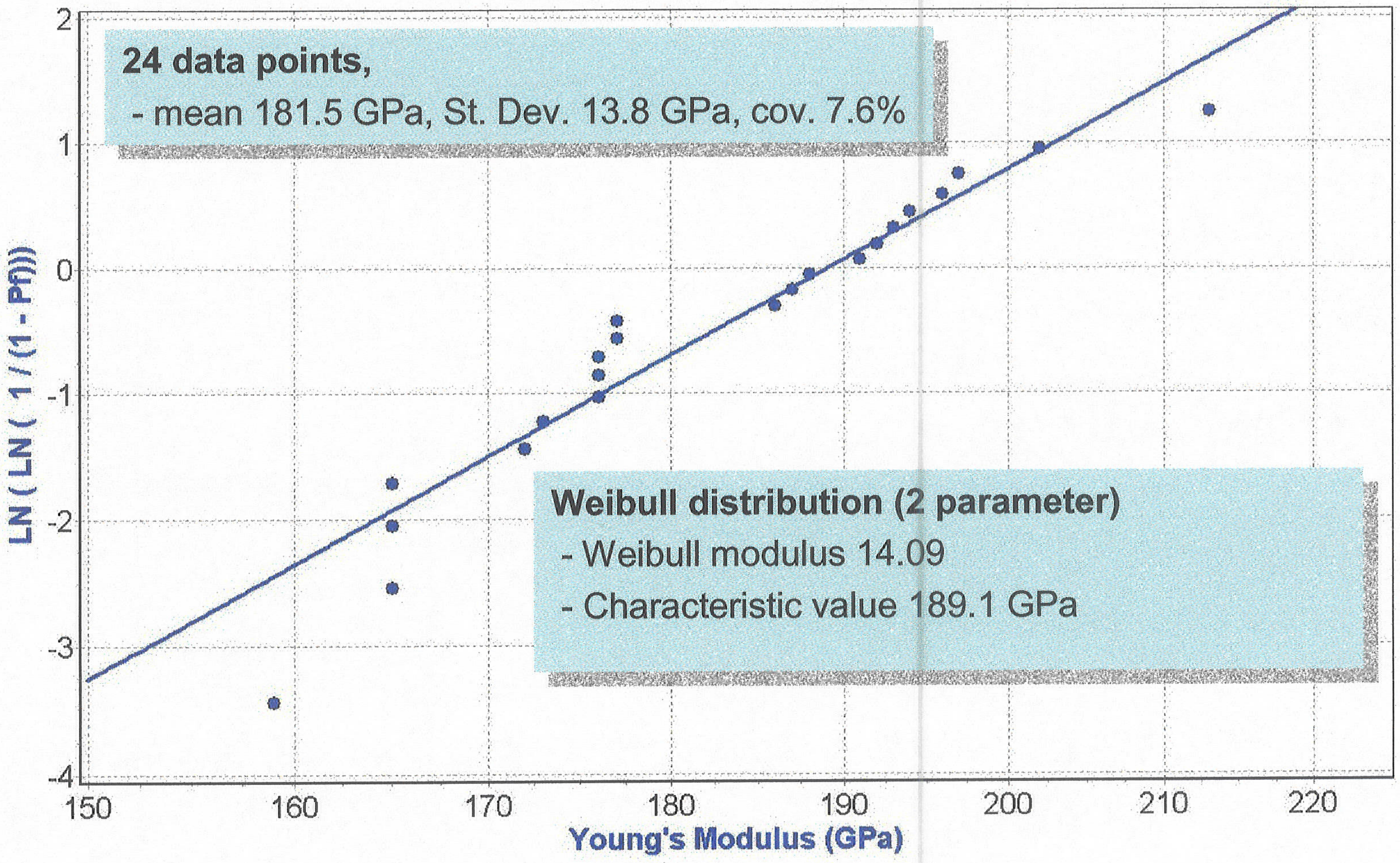
- Thermal/Stress Analysis of Turbine Vane



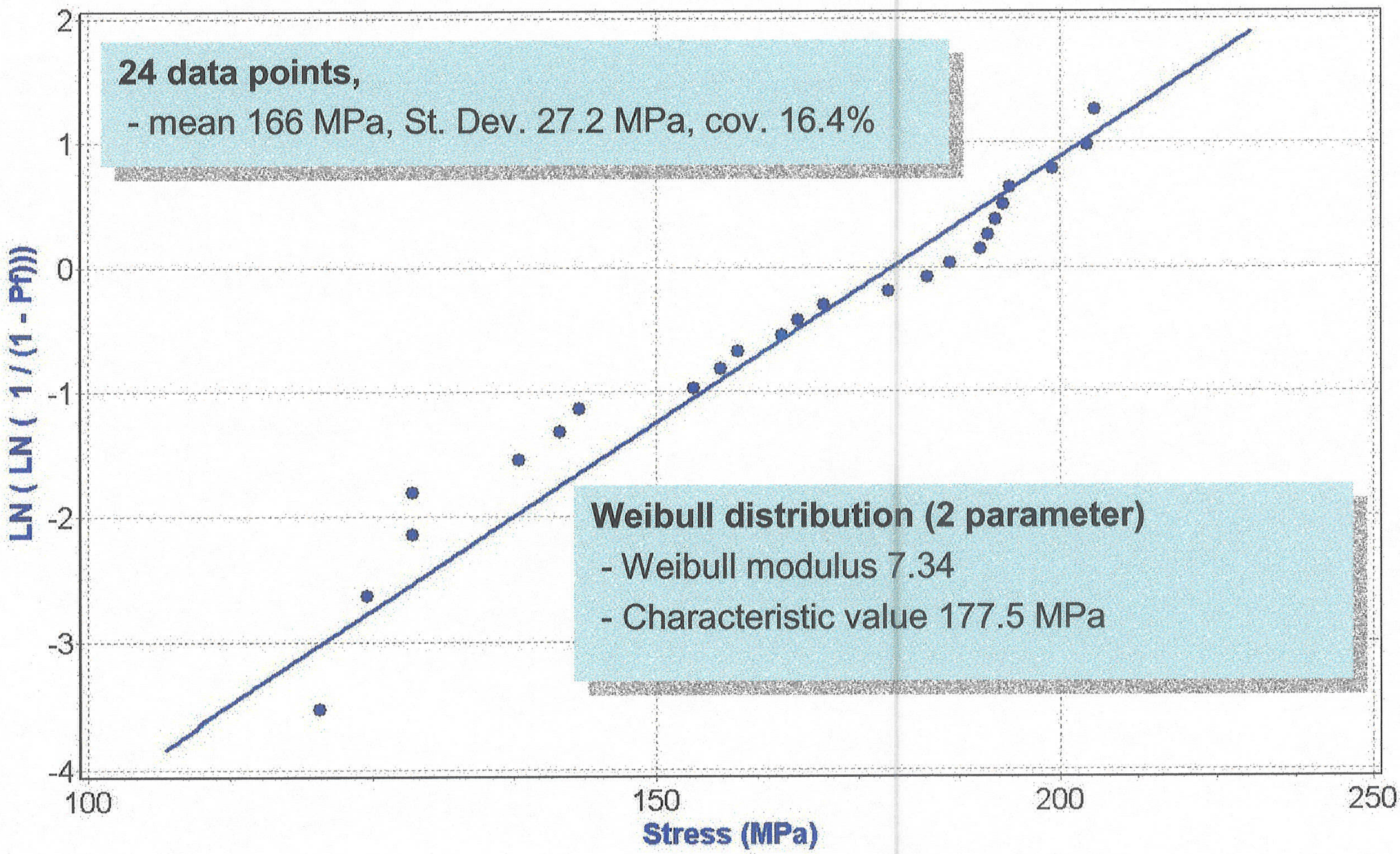
- 6 ply Sylramic Fiber Vane

- Hoop-stress for Mid-span

In-plane Modulus of MI SiC/SiC Material at 2200 ^{0}F



Proportional Limit of MI SiC/SiC Material at 2200 ^{0}F



Objectives

- Perform a formal risk assessment (using probabilistic methodology) of the all CMC turbine stator vane under high pressure burner rig conditions.
- Account for the observed scatter in material behavior (modulus and strength).
- Consider possible uncertainties in loading conditions (external and internal pressures), and other material properties (Poisson's ratios and thermal expansion coefficients.
  - *Note: Risk/failure for the present purposes is simply not meeting the design requirements. Vane is designed to assure that the stresses under rig conditions are always below the proportional limit*

Probabilistic Distribution Function Computational Details

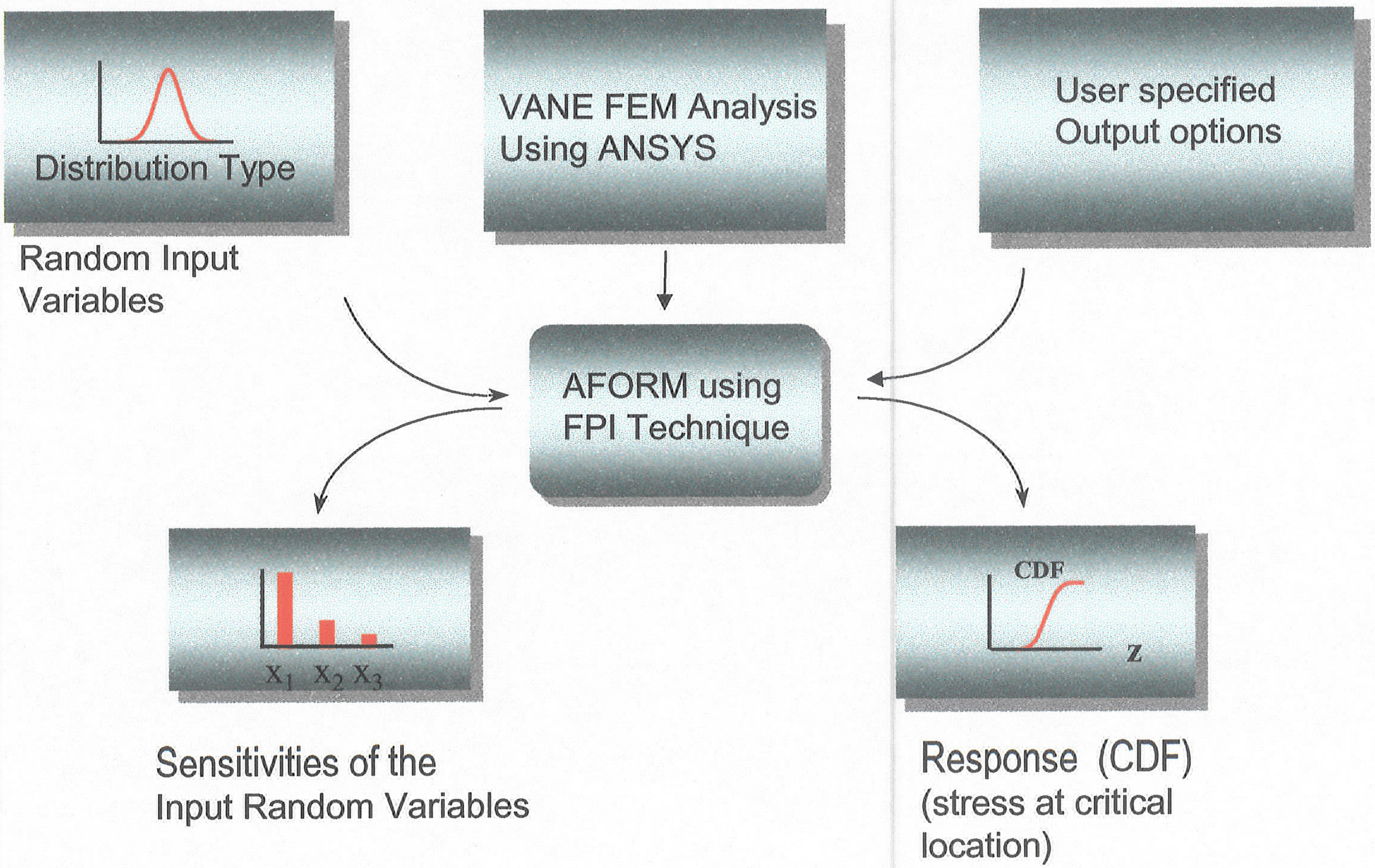
$$S(\underline{X}) = S(X_1, X_2, \ldots\ldots\ldots X_n)$$

$$g(\underline{X}) = g(R, S) = R - S$$

$$P_f = P[g(\underline{X}) \leq 0] = \int_{\Omega} \ldots \int f_x(x) dx$$

Where S is response variable (Stress at a critical location), $\underline{X}$ Input random variable vector (properties, geometry, loads, etc., P_f probability of failure, f_x joint probability density function

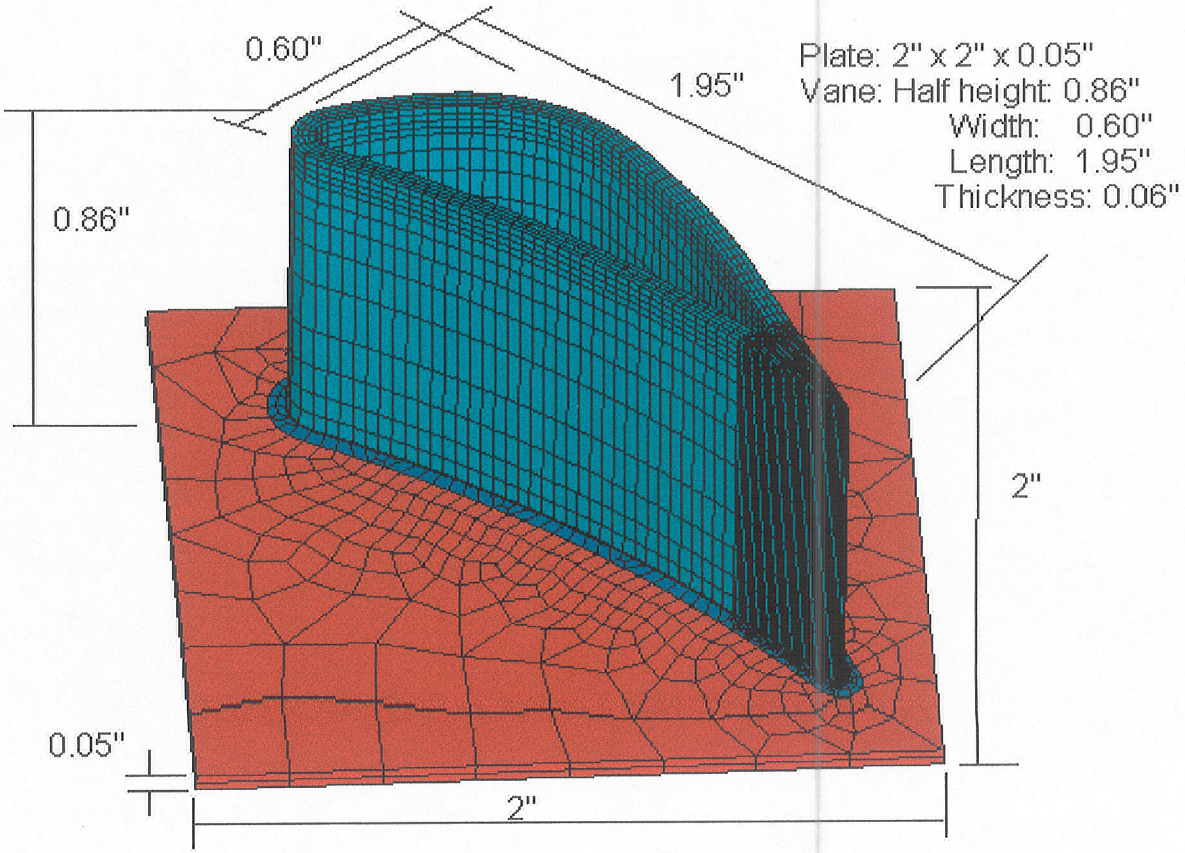
Reliability Assessment Flow Chart



Finite Element Model

Finite Element Model of a Stator Vane Test

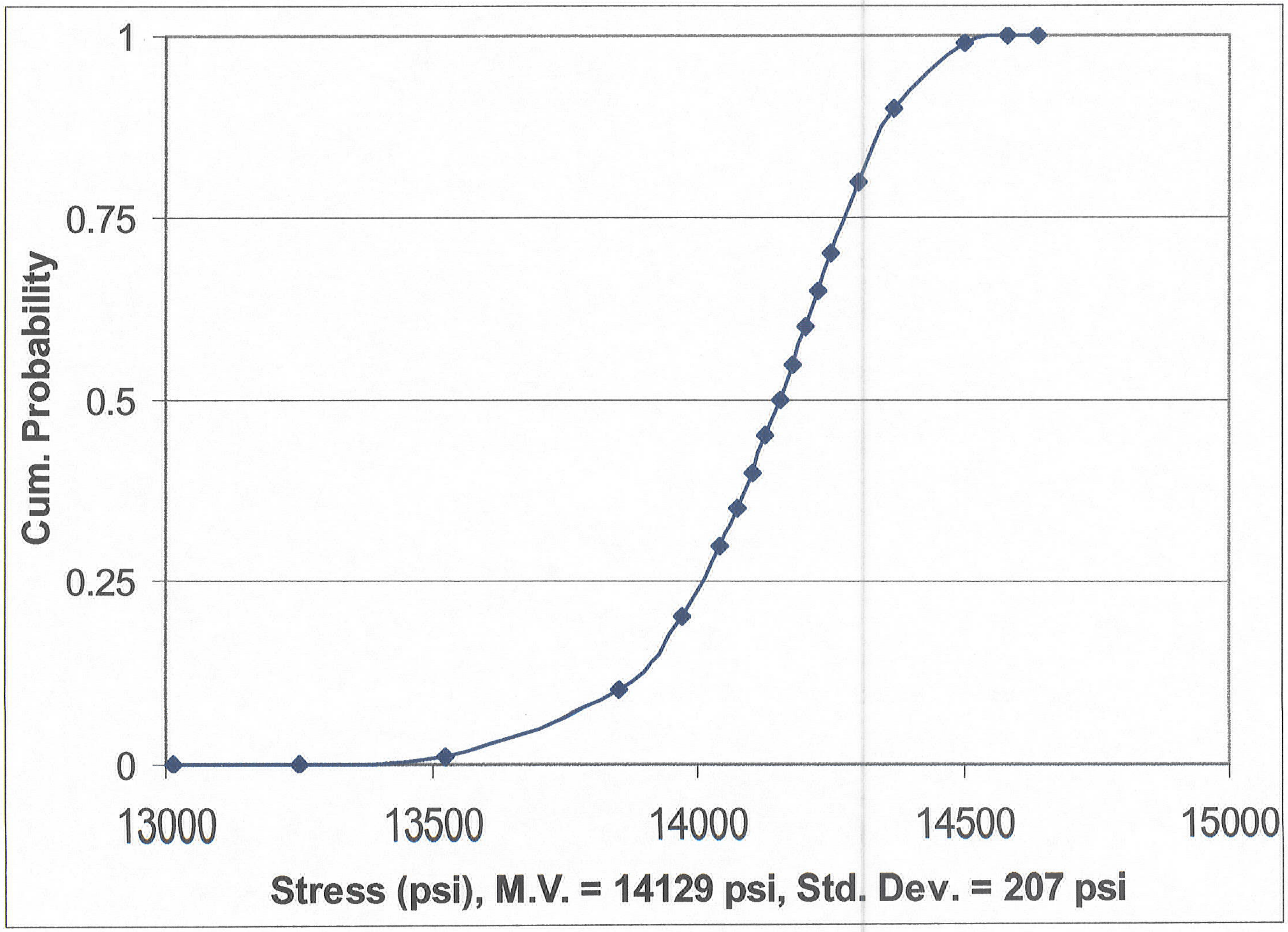
Nodes: 15,900; Elements: 12,385 Eight-Node Brick



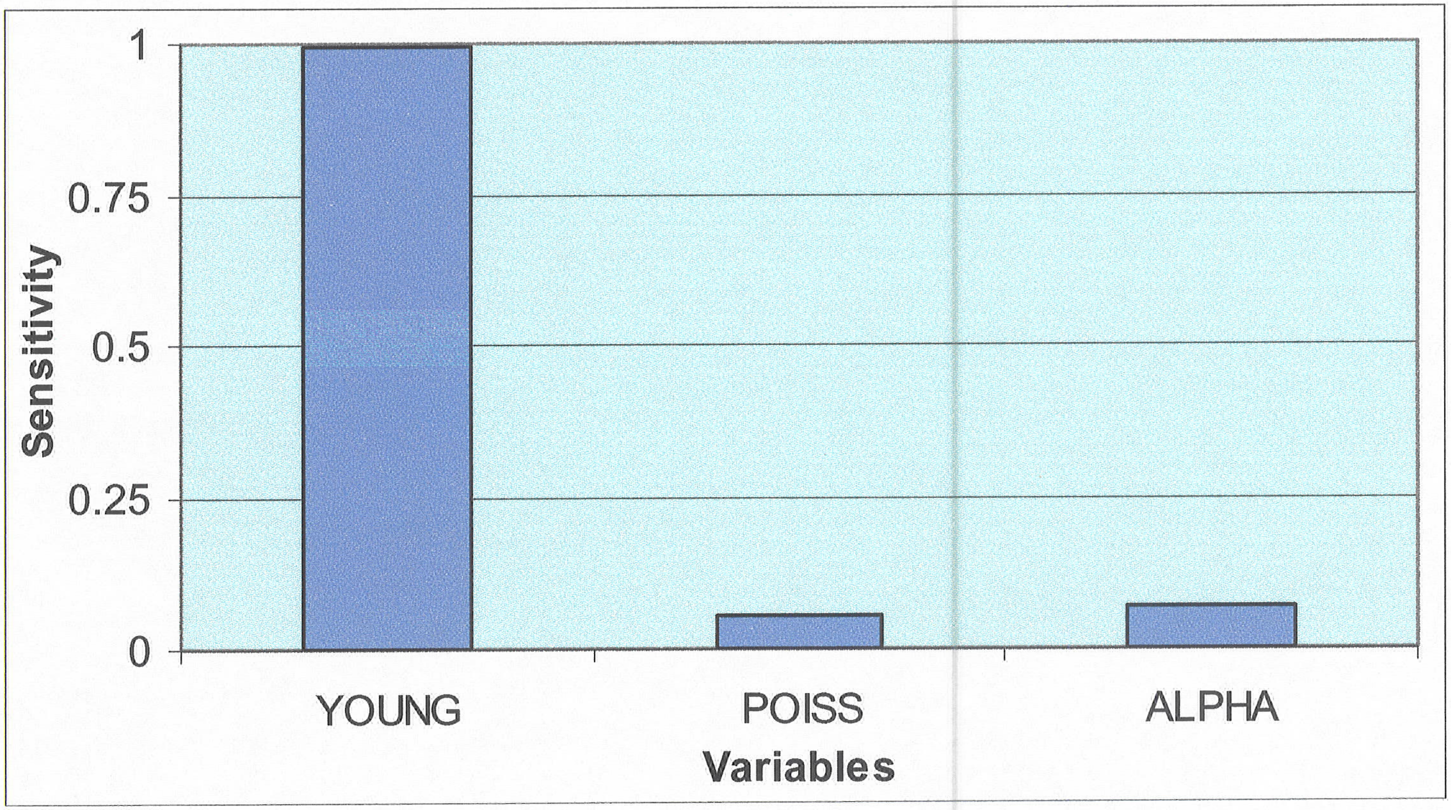
Cases Studied

1. Modulus, Poisson's Ratio, CTE's, and Strength are considered as input random variables
   - Modulus statistics are taken based on measured data
   - Poisson's ratio: Normal distribution with 2% coefficient of variation
   - Thermal expansion coefficients: Normal distribution with 8% variation
2. Two additional variables internal and external pressures added to the analysis
   - Internal pressure mean 125 psi, cov. 4%, Normal distribution
   - External pressure mean 80 psi, cov. 8%, Normal distribution

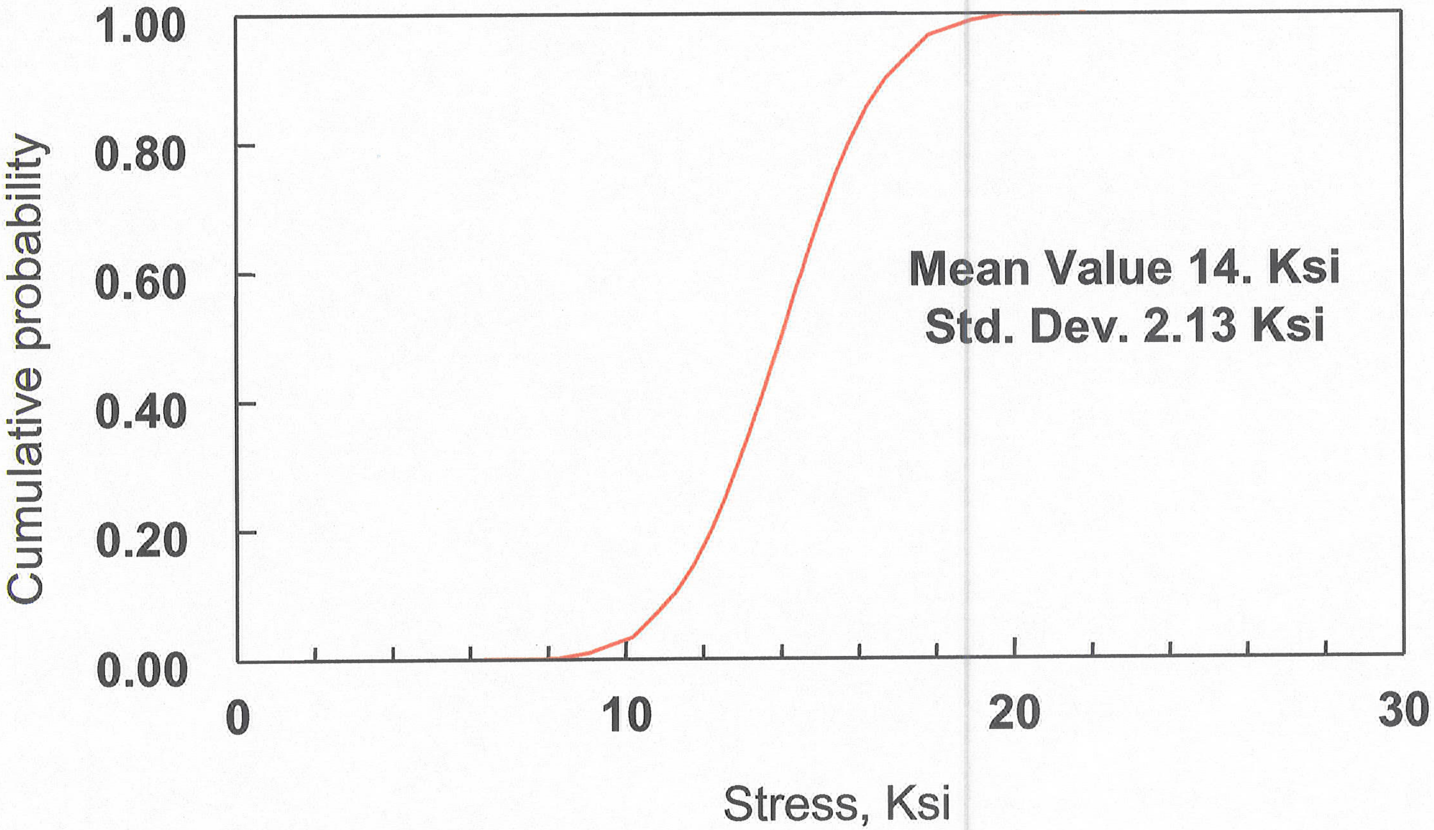
Case 1: CDF of Hoop Stress at the Critical Location



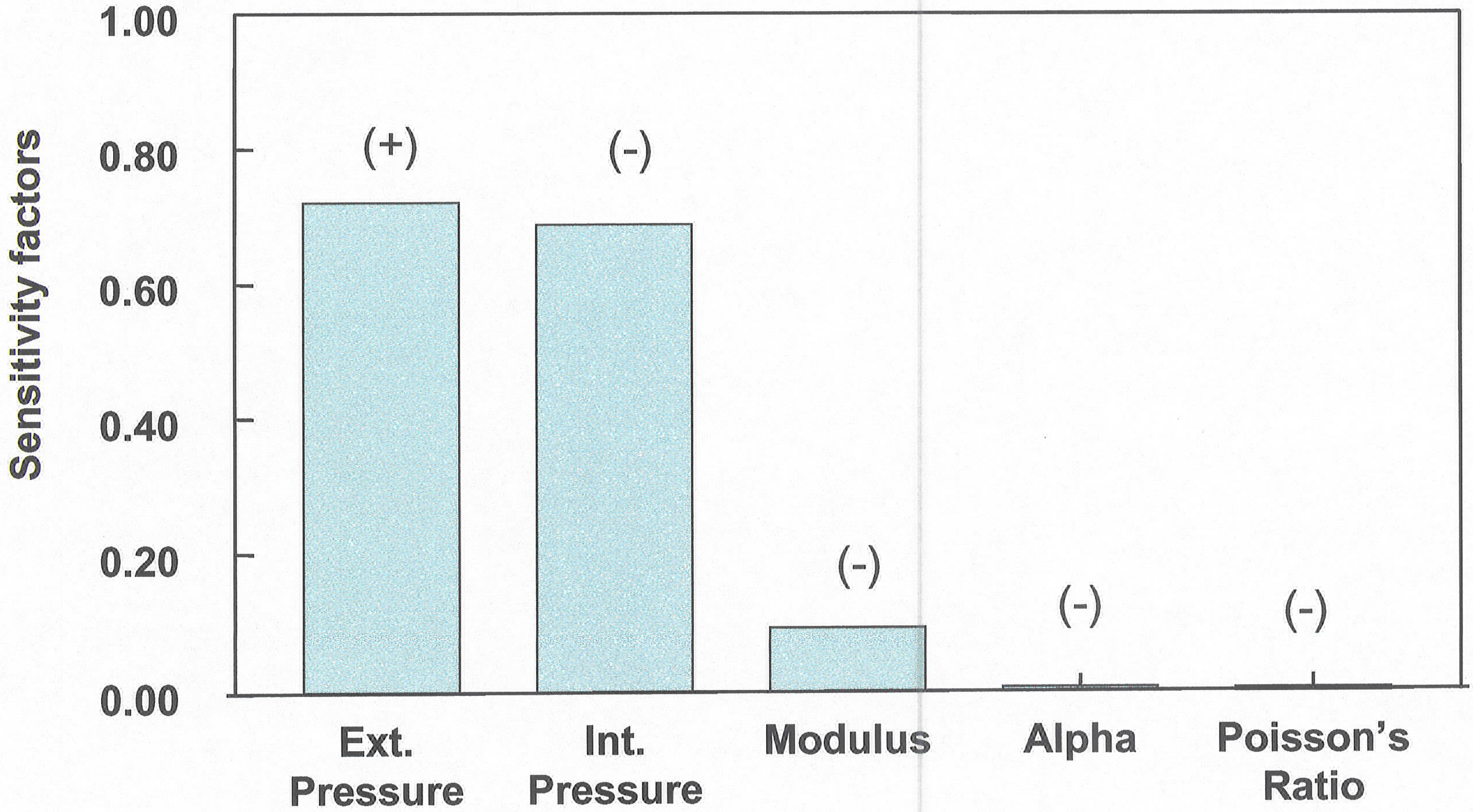
Sensitivity Factors for Hoop Stress



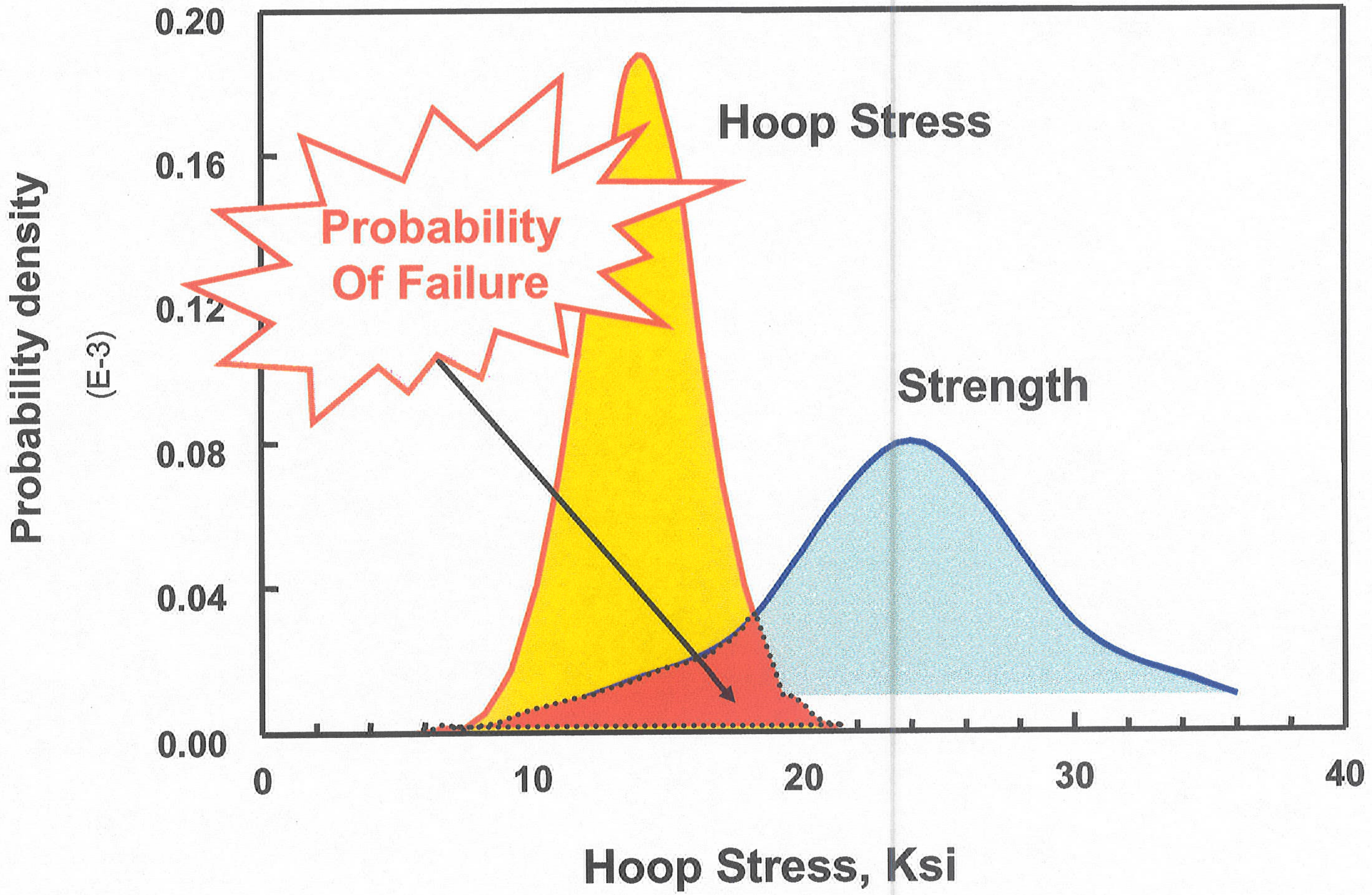
Case 2. CDF of Hoop Stress at Critical Location



Ranking of Scatter Causing Input Variables on Stress Response



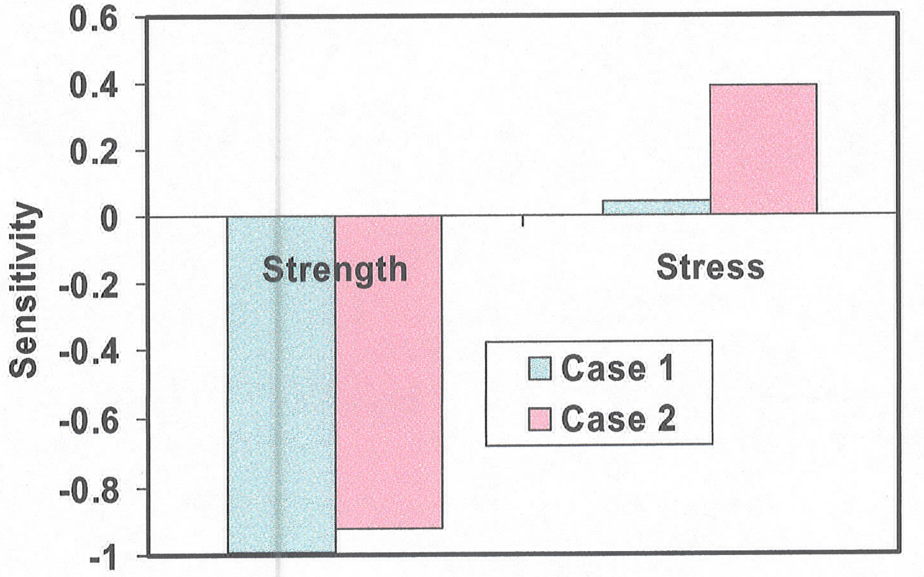
Risk Assessment Based on Failure to Meet Design Requirements



Risk Analysis

- g = R – S using Advanced First-order Reliability Method (AFORM)
- Case 1: P_f = 0.00994 (~ 1%)
- Case 2: P_f = 0.0162 (~ 1.6%)

Case	Failures
1	10/1000
2	16/1000



Summary and Future Plans

- **With the aid of ANSYS and In house computational tools a formal reliability assessment of an all CMC turbine stator vane is completed**
  - Two cases, one with 3 random variables and one with 5 random variables.
  - Case 2 showed that risk of not meeting the design requirements is about 16/1000
- **Results showed by far the loads have the most dominating effect on the critical location stress and material properties have minimal effect**
- **Scatter in strength is about the most important variable in dictating the reliability of the design.**
  - Improvements in fabrication can lead to reduction in the observed scatter in proportional limit thereby improving the reliability
  - Variability in critical stresses can be effectively controlled by having tighter controls in pressures.

Future Plans

- Thickness variations can have significant effects on stresses and must be considered in the analysis
- Temperature profile variations can affect thermally induced stresses and must be considered in the analysis
- We are looking into approximate methods to investigate thickness variation and thermal profile uncertainty effects on vane reliability
- Other vane configurations are also being investigated
- Vane life estimations