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Coupled Multi-Disciplinary Optimization for Structural Reliability and Affordability

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Abstract

A computational simulation method is presented for Non-Deterministic Multidisciplinary Optimization of engine composite materials and structures. A hypothetical engine duct made with ceramic matrix composites (CMC) is evaluated probabilistically in the presence of combined thermo-mechanical loading. The structure is tailored by quantifying the uncertainties in all relevant design variables such as fabrication, material, and loading parameters. The probabilistic sensitivities are used to select critical design variables for optimization. In this paper, two approaches for non-deterministic optimization are presented. The non-deterministic minimization of combined failure stress criterion is carried out by: (1) performing probabilistic evaluation first and then optimization and (2) performing optimization first and then probabilistic evaluation. The first approach shows that the optimization feasible region can be bounded by a set of prescribed probability limits and that the optimization follows the cumulative distribution function between those limits. The second approach shows that the optimization feasible region is bounded by 0.50 and 0.999 probabilities.

Introduction

Aircraft engines are assemblies of dynamically interacting components. Engine updates are required to keep aircrafts flying safely. In addition, engines for new aircrafts are progressively required to operate in a more demanding technological and environmental constraints. Designs to effectively meet those requirements are collections of multi-scale, multi-level, multidisciplinary analysis and optimization methods and probabilistic methods. These types of methods are necessary to quantify respective uncertainties and are the only ones that can formally evaluate advanced composite designs, which satisfy those progressively demanding requirements while assuring minimum cost, maximum reliability and maximum durability.

Recent research activities at NASA Glenn Research Center have focused on developing multi-scale, multi-level, multi-disciplinary analysis and optimization methods. Multi-scale refers to formal methods which describe complex material behavior; multi-level refers to integration of participating disciplines to describe a structural response at the scale of interest; multi-disciplinary refers to open-ended for various existing and yet to be developed disciplines. For example, these include but are not limited to: multi-factor models for material behavior, multi-scale composite mechanics, general purpose structural analysis, progressive structural fracture for evaluating durability and integrity, noise and acoustic fatigue, emission requirements, hot fluid mechanics, heat-transfer and probabilistic simulations. Many of these, as well as others, are encompassed in an integrated computer code identified as Engine Structures Technology Benefits Estimator (EST/BEST[1]). The discipline modules integrated in EST/BEST include: engine cycle (thermodynamics), engine weights, internal fluid mechanics, cost, mission and coupled structural\thermal, various composite property simulators and probabilistic methods to evaluate uncertainty effects (scatter ranges) in all the design parameters.

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The objective of the paper is to present methods\codes for simulating computationally the process of tailoring a hot composite engine structure in the presence of uncertainties in material fabrication, material thermo-mechanical properties, and loading. An internally pressurized CMC duct subjected to forced convection loading condition on its inner walls is used to illustrate its application to non-deterministic optimization. The respective variables are defined as primitive variables.

The EST/BEST (Engine Structures Technology Benefits Estimator) software, shown in figure 1, is used to carryout the investigative study presented in this paper. Component as well as system evaluations are performed within a single software. The modules included are integrated computer codes with multiple functional capabilities. The ones that were used for the results to be presented later are (1) Cosmo for finite element generation; (2) Material Library - for composite mechanics simulation; (3) IPACS[2] for composite structures probabilistic evaluation and (4) CSTEM[3] for coupled structural/thermal analysis and Optimization

Deterministic Coupled Structural/Thermal Analysis

A hypothetical engine duct made from woven fabric (Nextel 720 fiber and Aluminosilicate matrix) is modeled as a tube with a uniform wall thickness of 0.1" and mean height of 1.0". The Material Library in EST/BEST is used to estimate the balanced weave/thermal/mechanical properties of the composite system based on a fiber volume ratio of 0.45 and a void volume ratio of 0.1. The layup of the tube consists of 10 plies oriented as follows: $[2(0,90],0]_S$. The considered composite system is cured at a temperature of 300 F.

The coupled structural/thermal analysis of the CMC duct is carried out using the CSTEM code in EST/BEST. The duct is subjected to an internal pressure of 50 psig and forced convection on its inner walls. The forced convection is based on the flow of hot air through the duct at a velocity of 0.2 MACH and a convection temperature of 3000 F. On the outside of the duct, free convection at 70 F is considered. The structural deformation of the duct with internal pressure only is shown in Figure 2-a. The addition of the forced convection and its effect on the deformation of the duct is displayed in Figure 2-b. Note that the maximum displacement obtained with the application of combined thermo-mechanical loading is about eight times higher than that obtained with internal pressure only. The temperature distribution obtained for the composite duct from the coupled structural/thermal analysis is shown in figure 3. The temperature varied from 2935 F on the inner walls of the duct to 2821 F on the outside.

In CSTEM, the combined stress failure criterion is evaluated. The combined failure stress criterion is computed by summing various ply stresses to strength ratios. A failure function less than 1 indicates no failure, that equal to 1 indicates failure and greater than 1 indicates imminent failure.

Non-Deterministic Coupled Structural/Thermal Analysis

In EST/BEST, the IPACS module is used to perform probabilistic assessment of the composite structure. With the direct coupling of composite mechanics, structural analysis and probabilistic methods, IPACS is capable of simulating uncertainties in all inherent scales of the composite, from constituent materials to the composite structure and its loading conditions.

Figure 4 shows the probabilistic evaluation of the CMC duct under combined thermo-mechanical loading. The effects of uncertainties in composite material properties, composite fabrication parameters, and combined thermo-mechanical loading are assessed. The combined stress failure criterion is evaluated probabilistically based on the following scatter in primitive variables: ±5% in fiber and matrix moduli, and convection temperature; ± 10% in fiber and matrix thermal conductivity, matrix thermal expansion coefficient, matrix strength, fiber volume ratio and heat transfer convection coefficient; and ± 15% in fiber thermal expansion coefficient and fiber strength, void volume ratio, and internal pressure. The scatter ranges considered here are typical for the primitive variables selected in the study.

The results from the probabilistic evaluation are presented in Figure 4. Note that for a probability higher than 0.92, failure is imminent. The probabilistic sensitivities of the combined stress failure criterion to the scatter range of the primitive variables are presented in figure 5. The objective of this particular evaluation is to identify the primitive variables critical to the failure of the CMC duct. Based on the probabilistic sensitivity analysis, the list of critical primitive variables can now be reduced to include matrix modulus, matrix thermal expansion coefficient, matrix conductivity, matrix strength, fiber volume ratios, and void volume ratio. These set of primitive variables are used as design variables in the optimization. Although the primitive variables for loading show significant effects on the combined stress failure criterion, they are not included in optimization. These are assumed to be constant with values of their respective means.

Non-Deterministic Multi-disciplinary Optimization

Non-deterministic optimization may be defined as follows:

Find a set of primitive variables (those that describe the physics and can be varied by the designer such that some combined objective (merit) function is simultaneously minimized/maximized subject to probabilistically described variability in the primitive variables and in the constraints of the behavior (response) variables. In equation form the above statement is expressed thus:

Optimize: $\Im$ (P.V.) $\ni$ max (P_d) min (P_c) max (P_s) min (P_f) And $\ni$ $P_{lb} \leq (P.V.) \leq P_{ub}$

Where $\Im$ is the function to be optimized; P.V. are a set of primitive variables; the symbol $\ni$ denotes such that; P_d is the probability of durability; P_c is the probability of cost; P_s is the probability of survivability and P_f is the probability of failure. The non-deterministic evaluation pursuit consists of three different parts. Part one is probabilistic evaluation followed by optimization. Part two is optimization followed by probabilistic evaluation. Part three is the simultaneous evaluations as defined above. The work presented in this paper does not include the three-part evaluation study.

Note that the non-deterministic optimization is carried out based on a design (feasible) region that is constrained by the limits that are determined in the probabilistic evaluation. As indicated in figure 6, the feasible region bounds are represented by the limits set at high and low probability levels. Results for probabilistic evaluation followed by optimization and for optimization followed by probabilistic evaluation are discussed in the next two sections.

Probabilistic Evaluation of Failure Stress Followed by Optimization

It is instructive to illustrate non-deterministic multidisciplinary optimization by minimizing the maximum combined stress failure criterion of the CMC duct. First a probabilistic analysis of the structure is carried based on the following scatter in primitive design variables: ±5% in matrix modulus; ±10% in matrix thermal expansion coefficient, matrix thermal conductivity, matrix strength, and fiber volume ratio; and ±15% in void volume ratio.

Results from the probabilistic evaluation of the combined stress failure criterion based the aforementioned uncertainties are shown in figure 7. For probability value of 0.001 (1 occurrence in one thousand trials) the combined stress failure criterion of the composite duct would be under 0.357 (No ply failure). For probability value of 0.95, the failure function would be under 1.05 (ply failure has occurred). Optimization is than carried out to minimize the maximum combined failure stress criterion while constraining the first natural frequency of the structure. The design bounds lower and upper limits for optimization are set equivalent to the most probable design at probability levels of 0.001 and 0.95 respectively. Limits for the frequency constraint are set to those obtained probabilistically at the probability levels 0.001 and 0.95 (6517 to 8412 cps).

As shown in Figure 7, the optimization process that starts at 0.95 probability, follows the cumulative distribution function and reduces the objective function (maximum combined stress failure criterion) from 1.05 to 0.48. The actual frequency constraint at the end of optimization is about 7179 cps. Table 1 lists a summary of initial and optimum design variables and constraints, initial and optimum objective function, and the most probable design at 0.001 and 0.95 probability levels. Note that the largest variation is in the void volume ratio where it is reduced by more than 60% followed by the matrix strength which is lowered by more than 25%.

Optimization Followed by Probabilistic Evaluation

The maximum combined stress failure criterion of the CMC duct is minimized subject to frequency constraint. As shown in Table II, an initial design vector is selected and the optimization process is initiated according to the bounds prescribed in the Table. The upper and lower design bounds are computed based on the scatter in the design primitive variables. For example and as described in the previous section, the scatter in the matrix modulus is ±5% with a mean of 4.4 results in low and high bounds of 4.18 and 4.62 respectively. Note that the optimization reduced the objective function (combined stress failure criterion) from 0.910 to 0.563.

Results from probabilistic evaluation after the minimization of the combined stress failure criterion are shown in Figure 8. The feasible design region is bounded between 0.50 and 0.999 probabilities. In that region, the primitive variables are within the high and low bounds that defined in Table II. The probability of having a combined stress failure criterion less or equal to 0.55 is 0.50. Also, the probability of having a combined stress failure criterion less or equal to 0.89 is 0.999.

Concluding Comments

Important concluding comments from non-deterministic optimization results are:

1. The use of a collective multi-scale, multi-level, multi-disciplinary analysis and optimization and probabilistic methods shows that non-deterministic optimization can be done by performing probabilistic evaluation first then optimization or optimization first then probabilistic evaluation.

2. Performing probabilistic evaluation then optimization shows that the optimization follows the cumulative distribution function. The probabilistic evaluation is computationally more efficient than optimization. If the accuracy of the probabilistic response at extreme probabilities is improved, the use of optimization is not necessary.

3. Performing optimization then probabilistic evaluation shows that the optimization feasible region is bounded by 0.50 and 0.999 probabilities.

4. The probabilistic sensitivities can be used to select a reduced set of design variables for subsequent optimization.

References

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2. Chamis, C.C.; and Shiao, M.C.: IPACS – Integrated Probabilistic Assessment of Composite Structures: Code Development and Applications. Third NASA Advanced Composite Technology Conference, Vol. 1, Pt. 2, NASA CP-3178-VOL-1-PT-2, 1993, pp. 987-999.

3. Hartle, M.; and McKnight, R.L: CSTEM User Manual, NASA CR-2000-209308, January 2000.

Table I. Summary of Results From Probabilistic Evaluation Followed by Optimization

Design Variables	0.001 Prob	0.50 Prob	0.95 Prob	*Initial Design*	Optimum Design
Matrix modulus (Msi)	4.314	4.4	4.44	4.44	4.314
Matrix thermal expansion coeff. (x 1.0E-06 in/in/F)	3.059	3.25	3.35	3.35	3.059
Matrix thermal conductivity (BTU/hr-ft-F)	3.097	3.0	2.94	2.94	3.097
Matrix tensile strength (ksi)	15.81	13.0	11.84	11.84	15.81
Fiber volume ratio	0.399	0.45	0.479	0.479	0.399
Void volume ratio	0.071	0.100	0.116	0.1168	0.071
Objective					
Combined Stress Failure Criterion	0.3577	0.781	1.00	1.058	0.482
Constraint					
1st Natural Frequency (cps)	Limit set between 6517 and 8412			8116	7179

Table II. Summary of Results From Optimization Followed by Probabilistic Evaluation

Design Variables	Lower Bound	Upper Bound	Initial Design	Optimum Design
Matrix modulus (Msi)	4.18	4.62	4.62	4.18
Matrix thermal expansion coeff. (x 1.0E-06 in/in/F)	2.925	3.575	3.575	2.925
Matrix thermal conductivity (BTU/hr-ft-F)	2.70	3.3	3.30	3.30
Matrix tensile strength (ksi)	11.70	14.30	14.30	14.30
Fiber volume ratio	0.405	0.495	0.495	0.405
Void volume ratio	0.085	0.115	0.115	0.085
Objective				
Combined Stress Failure Criterion	0.712	0.910	0.910	0.563
Constraint				
1st Natural Frequency (cps)	Limit set between 6590 and 8357		8357	7187

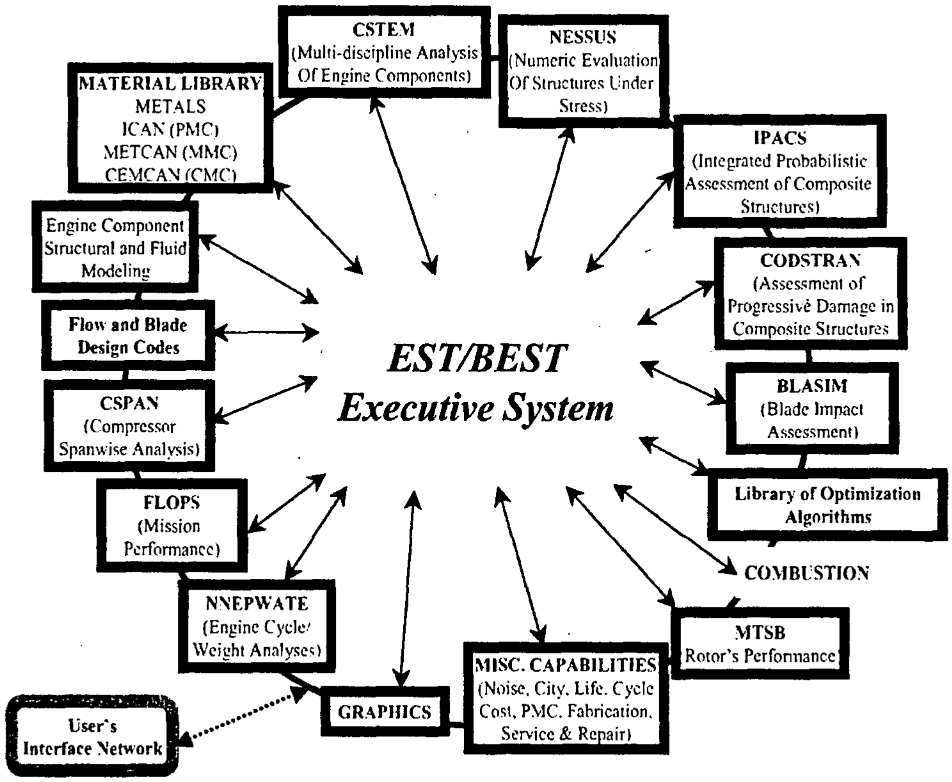
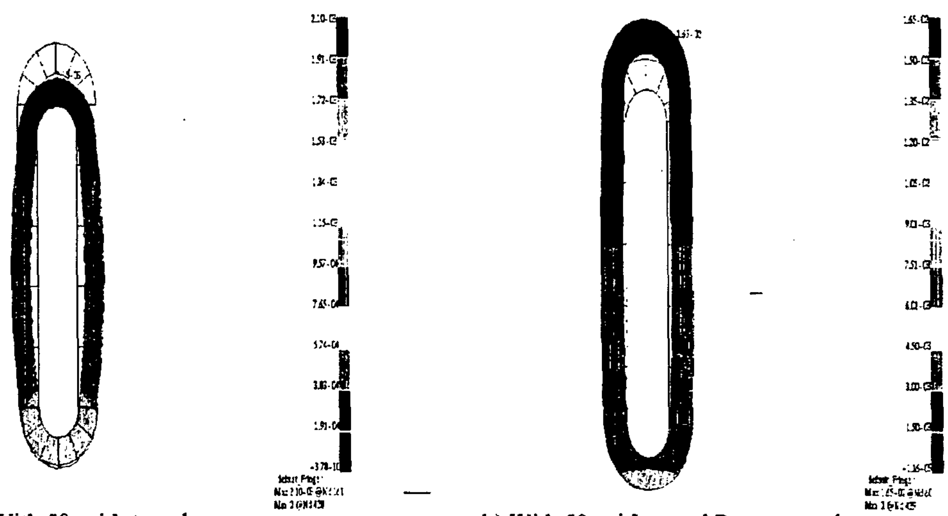


Figure 1. EST/BEST: Engine Structures Technology Benefit Estimator



a) With 50 psi Internal Pressure

b) With 50 psi Internal Pressure and Forced Convection

Figure 2. Displacement Fringe and Deformed Body Plots of CMC Duct

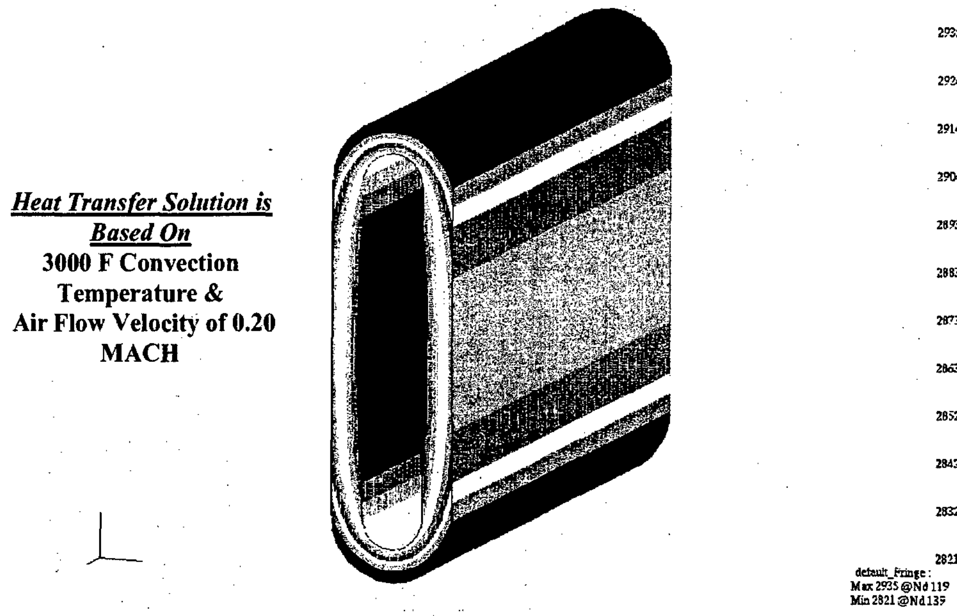


Figure 3. Temperature Plot of CMC Duct with Combined 50 psi Internal Pressure and Internal Forced Convection

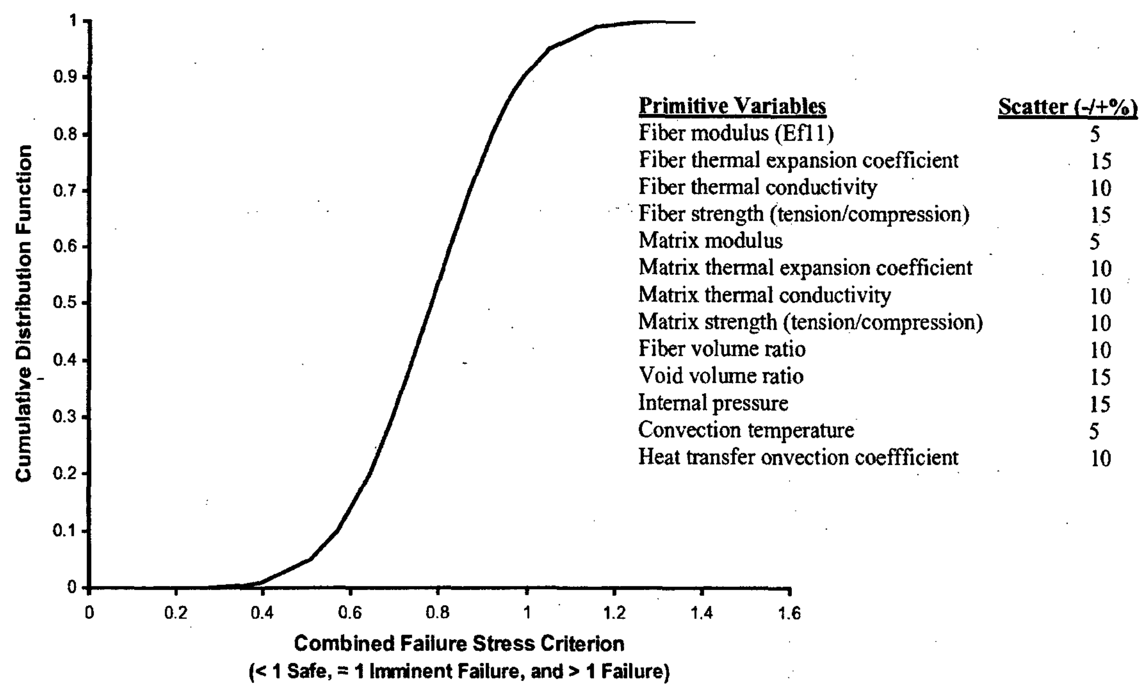


Figure 4. Probabilistic Evaluation of Combined Stress Failure Criterion of CMC Duct - With Combined Internal Pressure and Forced Convection

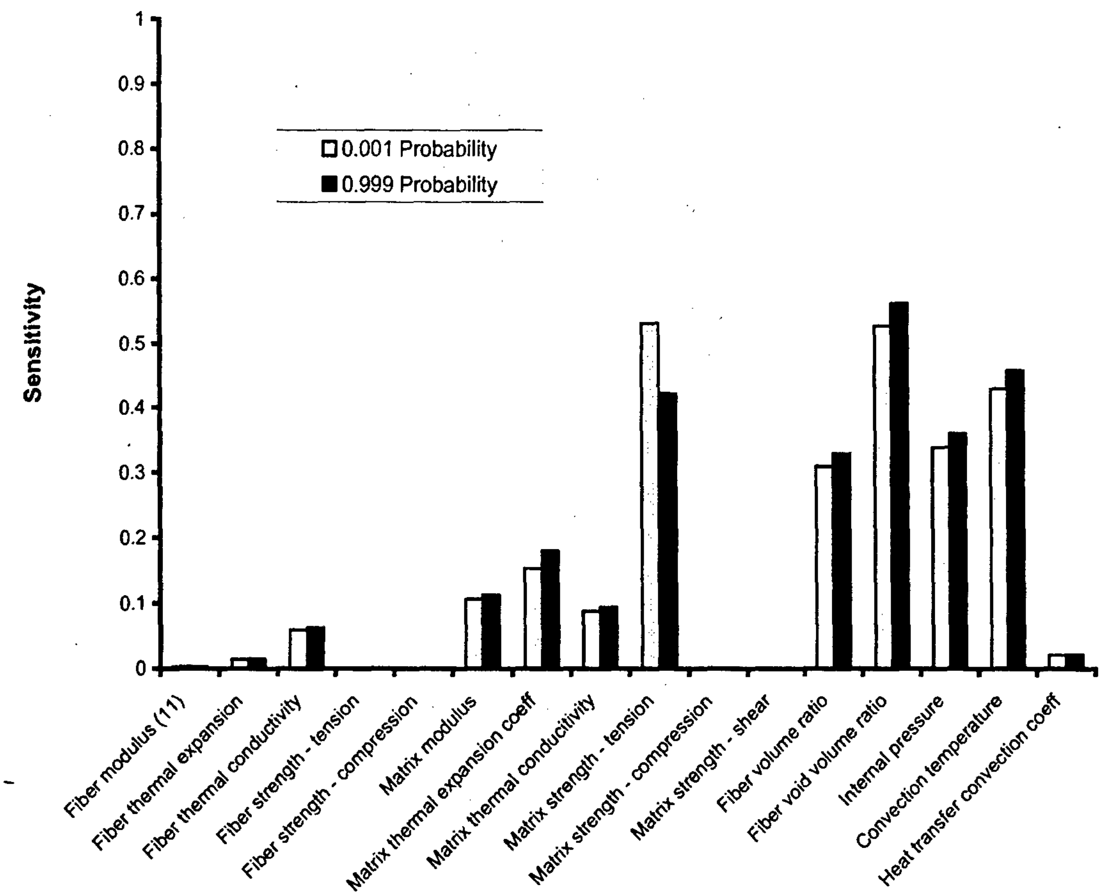


Figure 5. Sensitivity of Combined Stress Failure Criterion of CMC Duct to the Scatter Range - With Combined Internal Pressure and Forced Convection

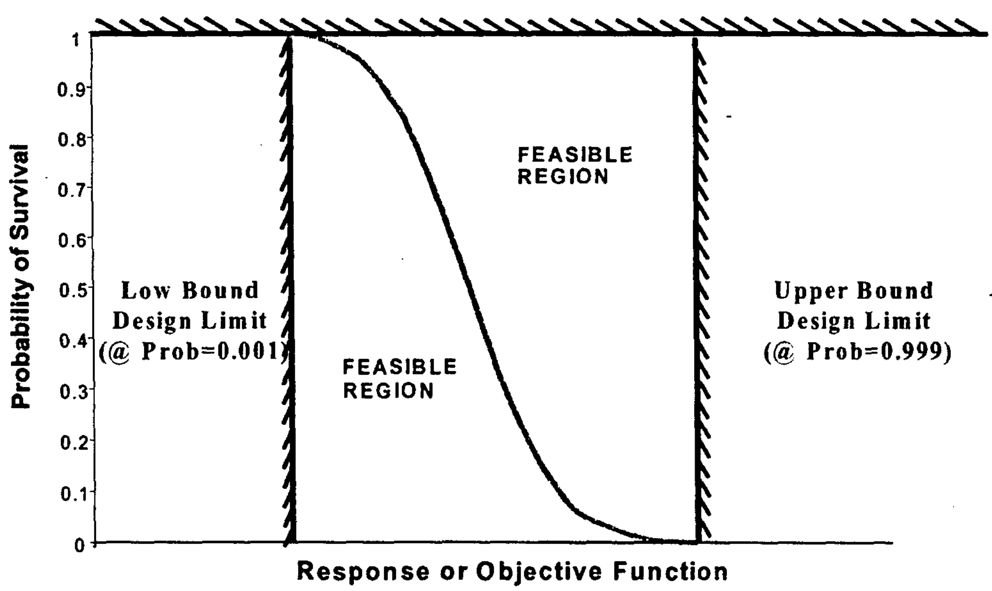


Figure 6. Optimization Feasible Region Based on Probabilistic Evaluation

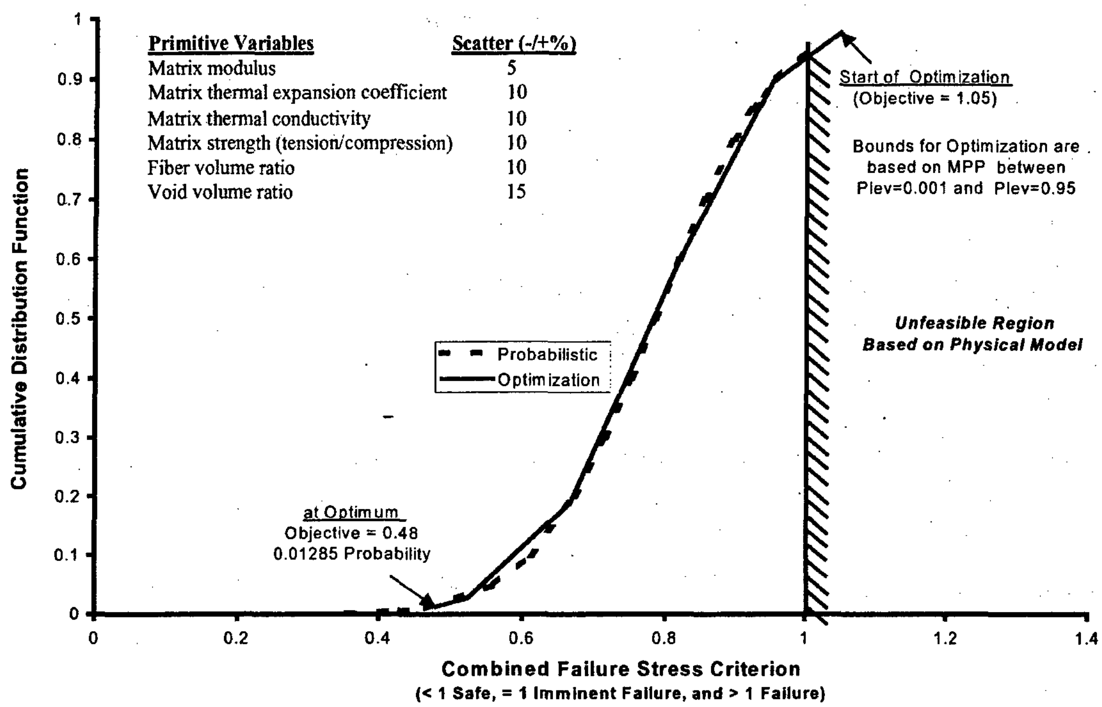


Figure 7. Probabilistic Evaluation of Combined Stress Failure Criterion Followed by Optimization (With Reduced Design Variables list)

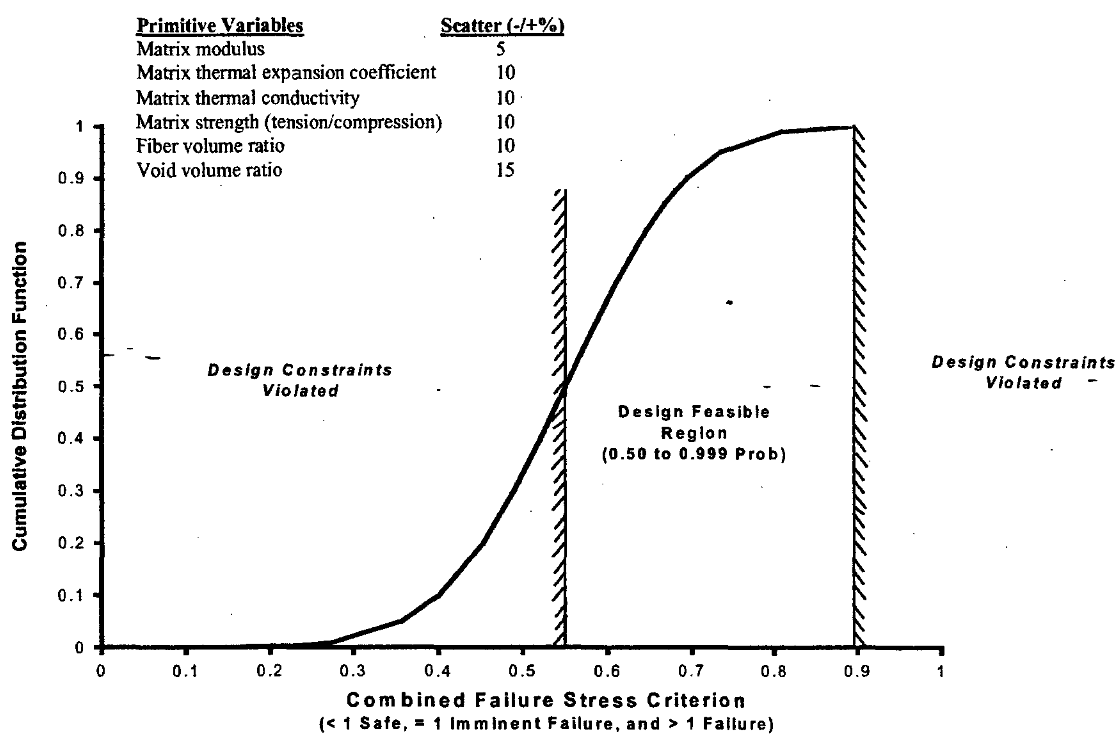


Figure 8. Probabilistic Evaluation After Minimization of Combined Stress Failure Criterion (Mean is Set Equal to Optimum Design)

Paper 5: Discussion

Question from H Pfoertner – MTU, Germany

What was the variation in loading and which optimisation method was used?

Presenter's Reply

In the probabilistic analysis, with the full set of primitive variables, variation in the internal pressure was +/-15% and variation of the convection temperature was +/-5% from their respective mean values. In the reduced set of primitive variables, only variations in the significant material and fabrication parameters were considered.

For the optimisation, a standard constrained minimisation code was utilised.

Question from M Botley – UK MoD

How were the data and the predictions of the model validated and how mature do you consider the technique to be?

Presenter's Reply

Computational simulation packages comprising the EST/BEST system, in particular the CSTEM and IPACS codes described in this paper, have been extensively validated with test cases over the last twelve years. The particular CMC duct structure presented here is a hypothetical example that was used to demonstrate the probabilistic optimisation methods.