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ICM11

## Coupled multi-disciplinary methods 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, results of the non-deterministic optimization are presented with probabilistic lower bounds of 0.001 and upper bounds of 0.999

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*Keywords:* Aerospace, Composite Components, Thermal Analysis, Structural Analysis

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### 1. Introduction

Recent research activities 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. The EST/BEST (Engine Structures Technology Benefits Estimator) software, shown in Fig. 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 tructures probabilistic evaluation and (4) CSTEM [3] for coupled structural/thermal analysis and Optimization.ages and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

## 2. 2. 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. The temperature distribution obtained for the composite duct from the coupled structural/thermal analysis is shown in Fig. 2.

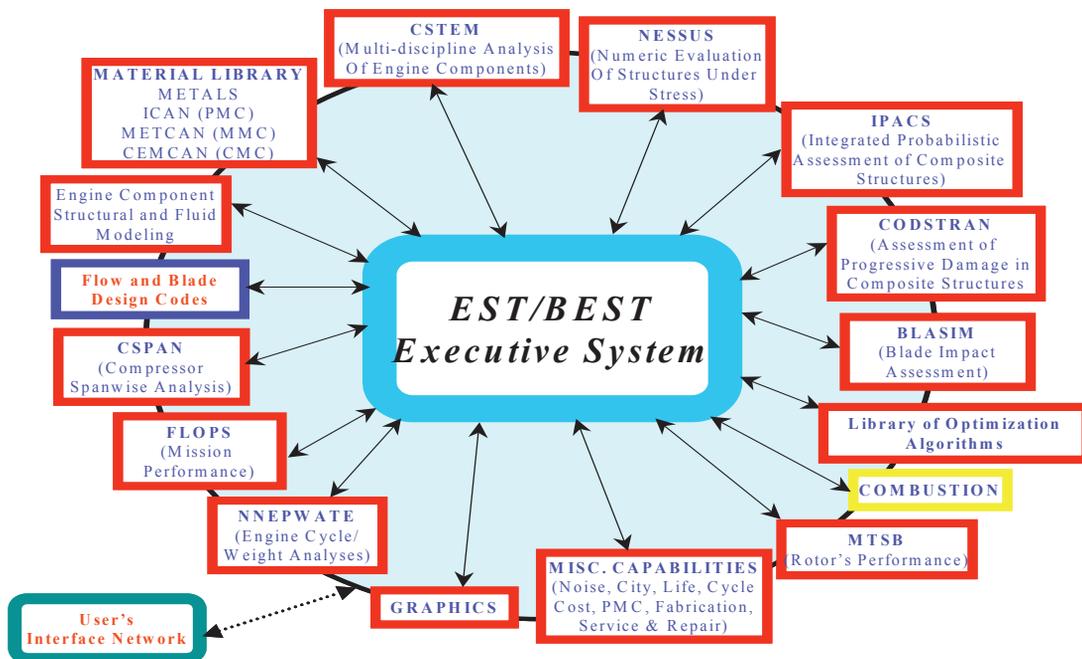


Figure 1. EST/BEST: Engine Structures Technology Benefit Estimator

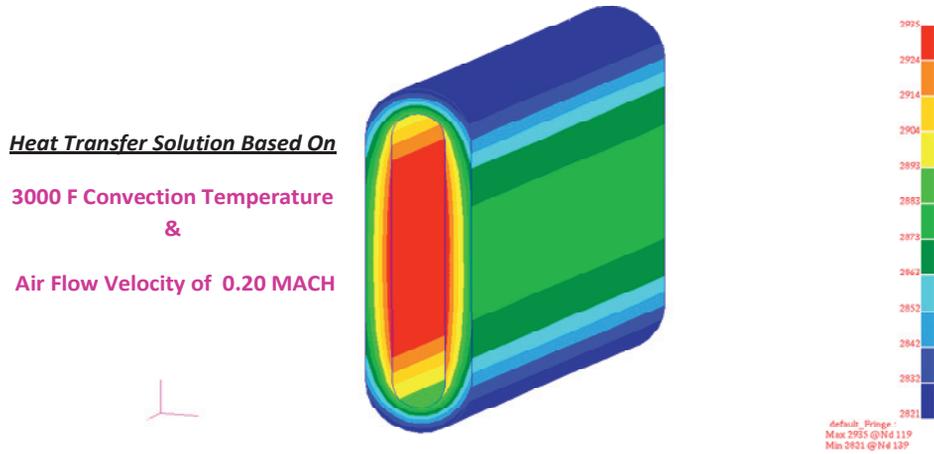


Figure 2. Temperature Plot of CMC Duct with Combined 50 psi Internal Pressure and Internal Forced Convection

The temperature varied from 1633C (2935<sup>0</sup>F) on the inner walls of the duct to 1547C (2821<sup>0</sup>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, equal to 1 indicates failure is imminent and greater than 1 indicates failure. Figure 3 shows the probabilistic evaluation of the CMC duct under combined thermo-mechanical loading.

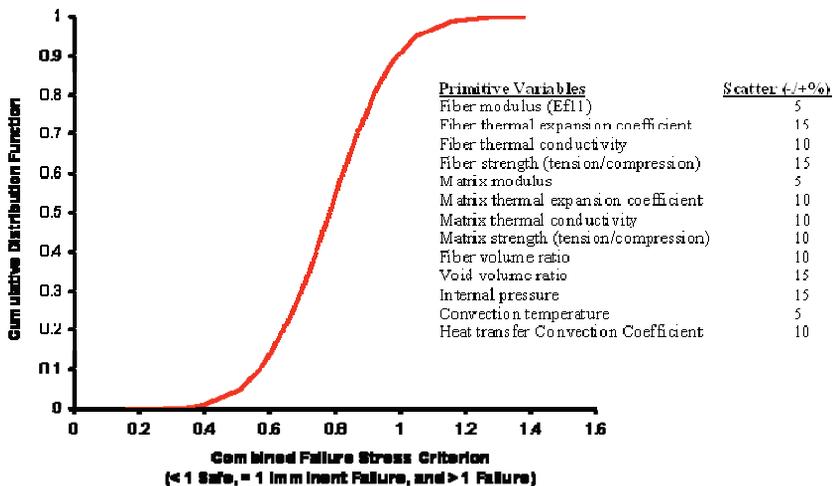


Figure 3. Probabilistic Evaluation of Combined Stress Failure Criterion of CMC Duct – with Combined Internal Pressure and Forced Convection

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:  $\pm 5\%$  in fiber and matrix moduli, and convection temperature;  $\pm 10\%$  in fiber and matrix thermal conductivity, matrix thermal expansion coefficient, matrix strength, fiber volume ratio and heat transfer convection coefficient; and  $\pm 15\%$  in fiber thermal expansion coefficient and fiber strength, void volume ratio, and internal pressure, Table 1. The scatter ranges considered here are typical for the primitive variables selected in the study. The results from the probabilistic evaluation Fig.3 show that 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 Fig. 4. These 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 because they assumed to be constant

Table 1. Summary of results from probabilistic evaluation followed by optimization

<b>Design Variables</b>	<b>0.001 Prob</b>	<b>0.50 Prob</b>	<b>0.95 Prob</b>	<b>Initial Design</b>	<b>Optimum Design</b>
Matrix Modulus (Msi)	4.314	4.4	4.44	4.44	4.314
Matrix Thermal Expansion Coefficient (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
<b>Objective</b>					
Combined Stress Failure Criterion	0.3577	0.781	1.00	1.058	0.482
<b>Constraint</b>					
1 <sup>st</sup> Natural Frequency (cps)	Limit set between 6517 and 8412			8116	7179

One Msi=6.9GPa; degree  $^{\circ}$ F=5/9C;ksi=6.9MPa; Btu=1055.1Joules

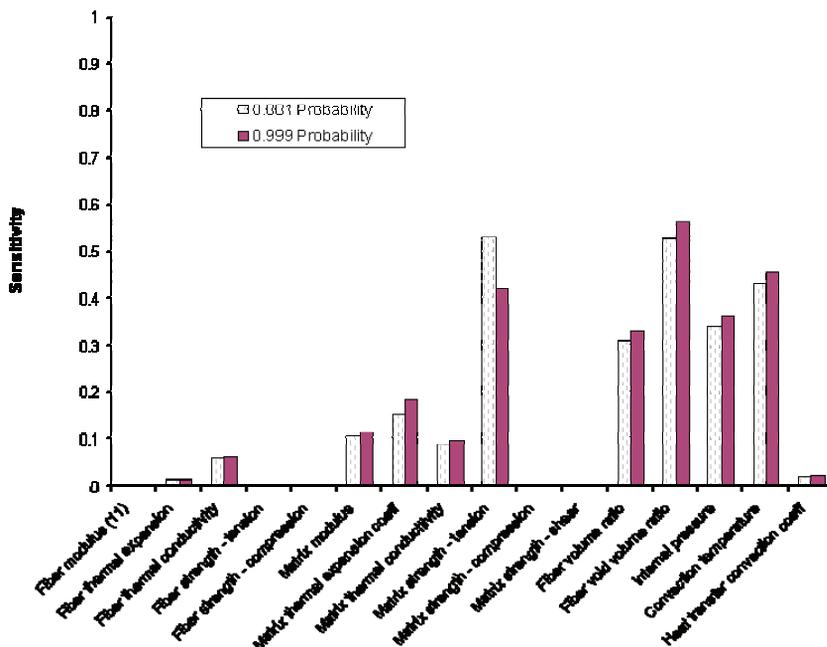


Figure 4. Sensitivity of combined stress failure criterion of CMC duct to the scatter Range with Combined internal pressure and forced convection

### 3. 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:

$$\text{Optimize: } \mathfrak{F} (P.V.) \ni \max (P_d) \min (P_c) \max (P_s) \min (P_f) \text{ And } \ni P_{lb} \leq (P.V.) \leq P_{ub} \quad (1)$$

Where  $\mathfrak{F}$  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. 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, Table 2. As indicated in Fig. 5, the feasible region bounds are represented by the limits set at high and low probability levels.

Table 2. 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 Coefficient (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
<b>Objective</b>				
Combined Stress Failure Criterion	0.712	0.910	0.910	0.563
<b>Constraint</b>				
1 <sup>st</sup> Natural Frequency (cps)	Limit set between 6590 and 8357		8357	7187

Msi=6.9GPa; 0F=%/(C; Ksi=6.9MPa; Btu=1055.1Joules

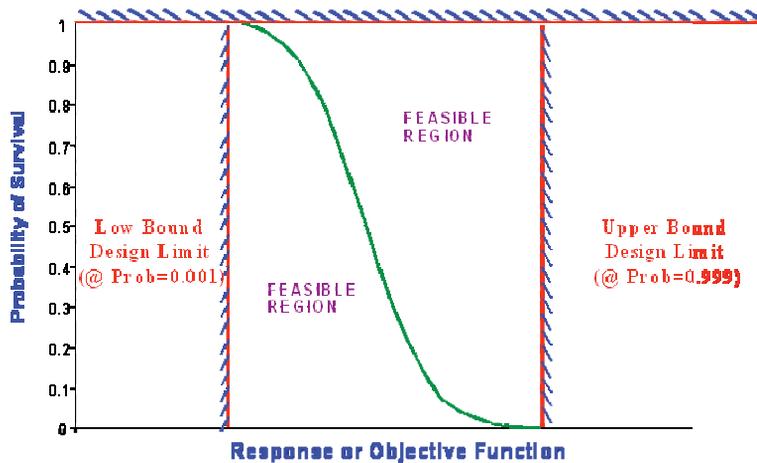


Figure 5. Probabilistic evaluation of combined stress failure criterion followed by optimization (with reduced design variables list)

#### 4. Concluding comment

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

#### Acknowledgements

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