Coupled multi-disciplinary methods for structural reliability and affordability

C. C. Chamis
NASA Glenn Research Center, Cleveland, USA

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.
Keywords: applications-aerospace, composite components, thermal analysis, structural analysis, probability, ceramic composites.

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

WIT Transactions on The Built Environment, Vol 125,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/OP120031

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 carry out 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.

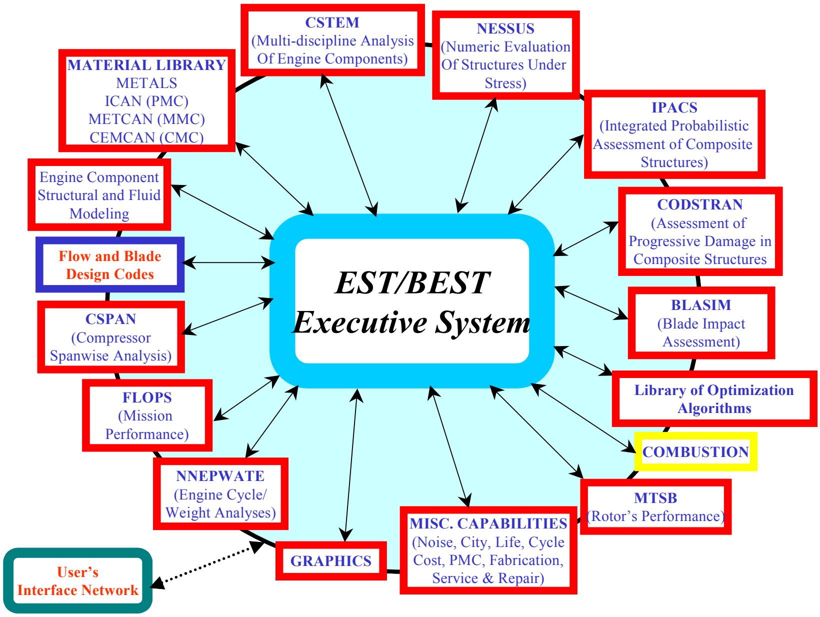

Figure 1: EST/BEST: Engine structures technology benefit estimator.

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.

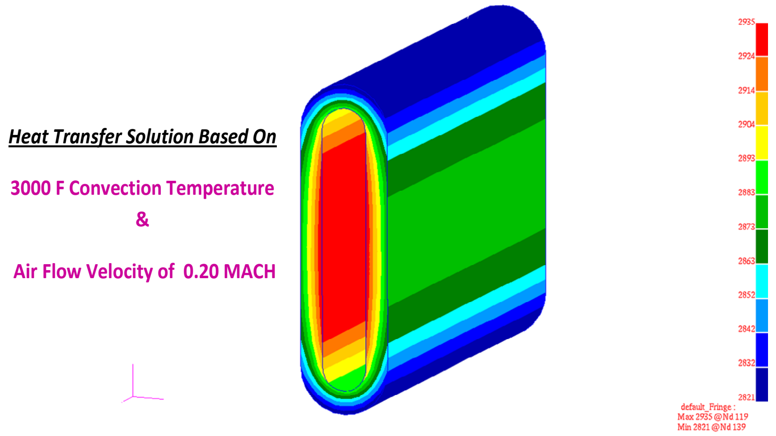

Figure 2: Temperature plot of CMC duct with combined 50 psi internal pressure and internal forced convection.

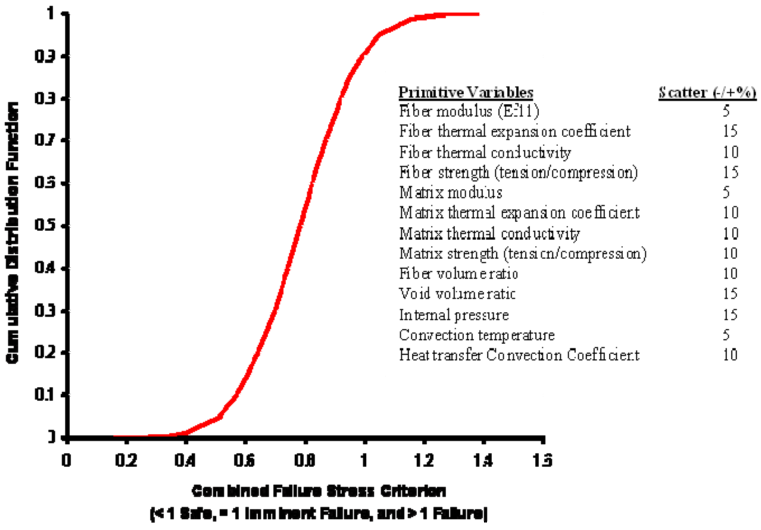

Figure 3: Probabilistic evaluation of combined stress failure criterion of CMC duct with combined internal pressure and forced convection.

The temperature varied from 1633C (2935^{0}F) on the inner walls of the duct to 1547C (2821^{0}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 than1 indicates failure. Figure 3 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, Table 1.

Table 1: 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 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
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

One Msi=6.9GPa; degree ^{0}F=5/9C:ksi=6.9MPa; Btu=1055.1Joules

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.

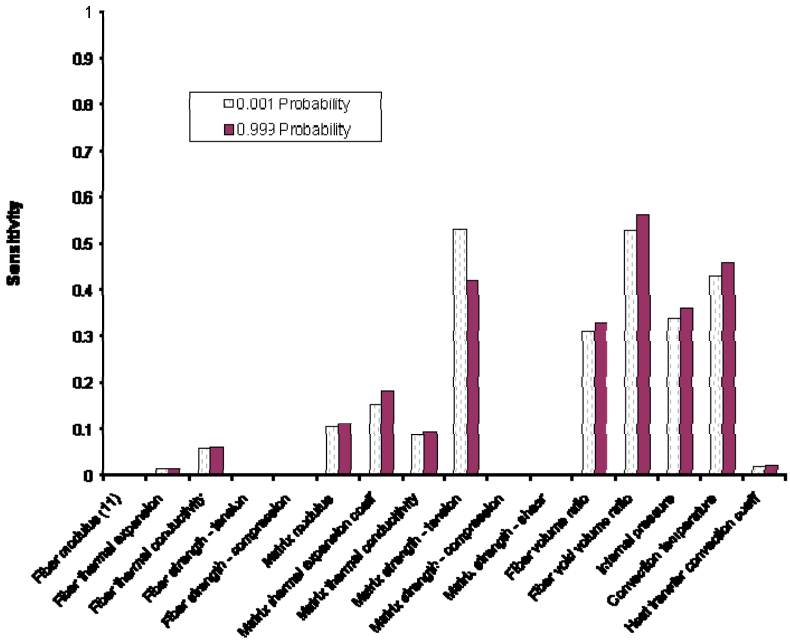

Figure 4: Sensitivity of combined stress failure criterion of CMC duct to the scatter range with combined internal pressure and forced convection.

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:

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

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. 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
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

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

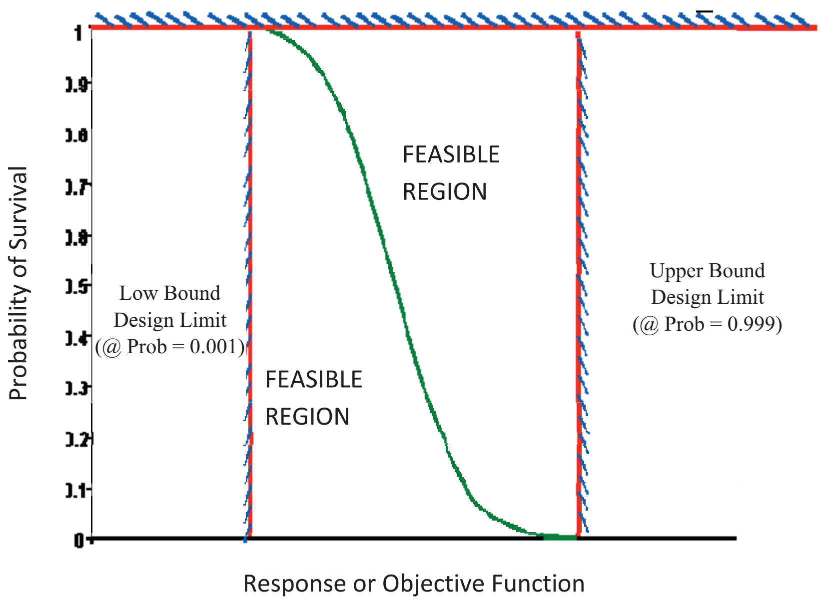

Figure 5: Probabilistic evaluation of combined stress failure criterion followed by optimization (with reduced design variables list).

4 Conclusions

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.

Acknowledgement

This paper is declared a work of the U.S. Government and it is not subject to copyright protection.

References

[1] Abumeri, G.H. and Chamis, C.C.: T/BEST a computer code for assessing the benefits of advanced aerospace technologies, published in the Advances in Engineering Software Journal, pp.231-238, 1997 Elsevier Science Limited, Printed in Great Britain.

[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.