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PROBABILISTIC DAMAGE PROGRESSION IN COMPOSITE STRUCTURES FOR NUCLEAR POWER PLANTS

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OBJECTIVES

- **Investigate durability of specialized ceramic matrix composite (CMC) structural systems exposed to nuclear radiation at elevated temperatures**
- **Cost effectively simulate degradation of CMC structures and predict the probability of failure under mechanical loading in a sustained radiation environment at high temperatures**
- **Consider effects of uncertainties in material and composite characteristics on structural response**
- **Determine sensitivity of structural durability to design variables**

NEED

- **Applications of SiC/SiC composites at high temperature and radiation require reliable performance for continuous service.**
- **It is necessary to quantify the level of structural safety after damage initiation and damage growth.**
- **The relationship between effects of damage evolution on structural response and remaining reliable life need be established for the in-service structural health monitoring of nuclear power plants.**

BACKGROUND

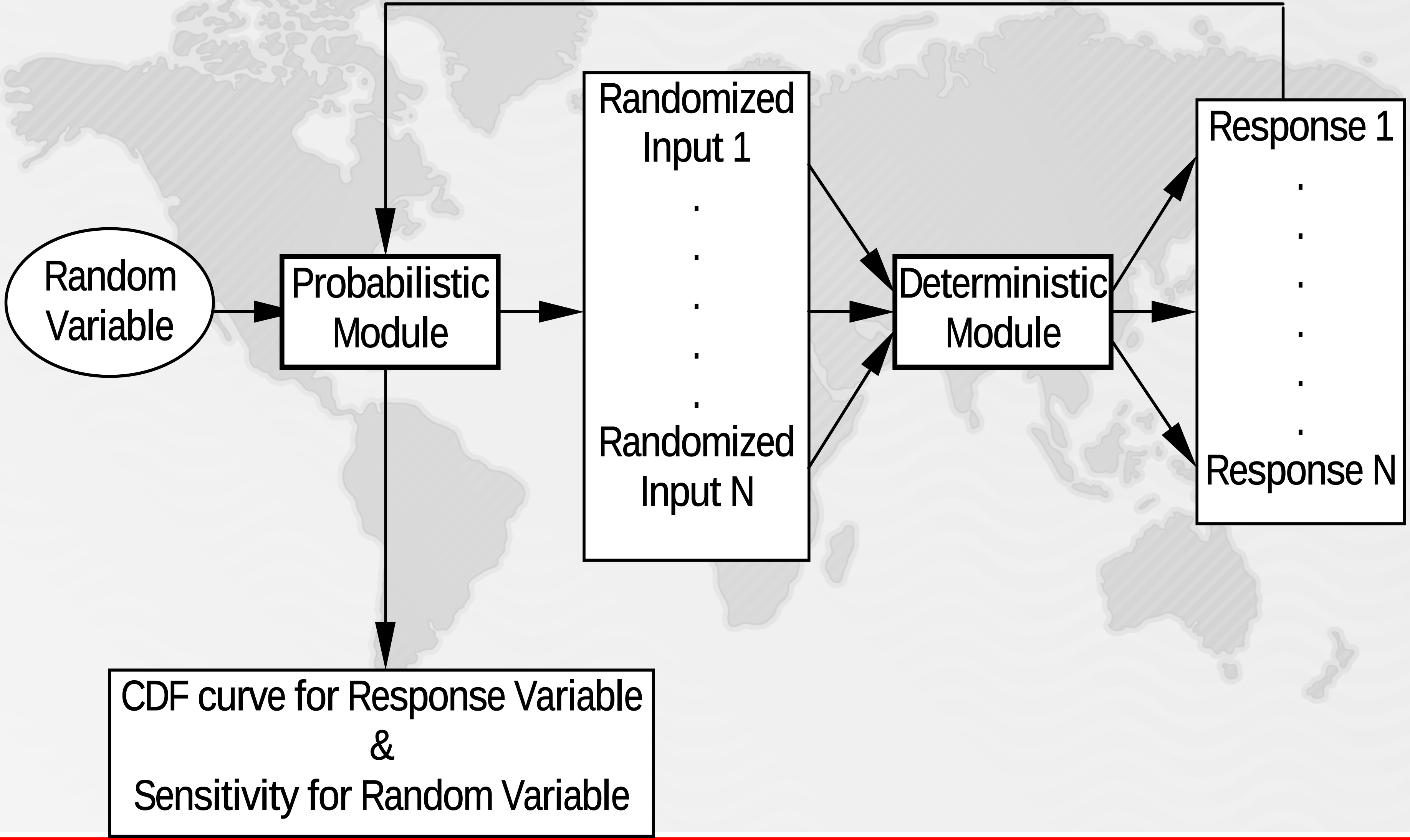
- Damage initiation, growth, accumulation, and propagation to fracture are important stages in evaluating the load carrying capacity and reliability of composite structures.

- Quantification of the structural fracture resistance is required to evaluate the durability/life of composite structures.

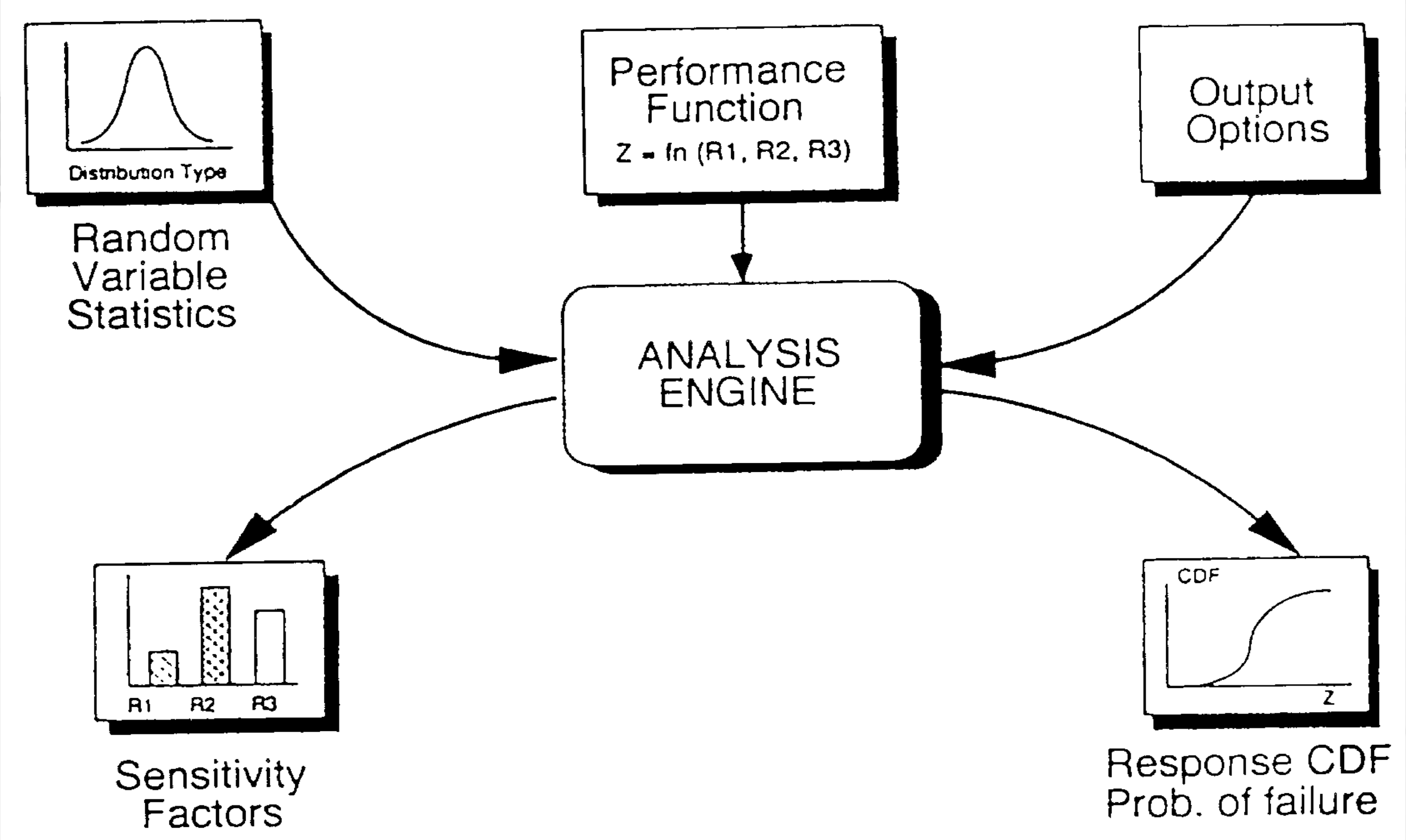
- A computational simulation method has been developed for this purpose.

- The method is able to simulate damage initiation, damage growth, and fracture in composites under many different types of loading, and temperatures, considering also the effects of a radiation environment.

Integration of Probabilistic Analysis with Progressive Fracture



Schematic of Probabilistic Analysis Module



Progressive Fracture Simulation Methodology

- Computational simulation is implemented by the integration of three computer codes: (1) composite mechanics, (2) finite element analysis, and (3) damage progression tracking.

- The damage progression module keeps track of composite degradation for the entire structure.

- The composite mechanics code is used for composite micromechanics, macromechanics, laminate analysis, as well as radiation and high temperature exposure durability analysis.

- The finite element analysis module that anisotropic thick shell and 3-D solid elements to model laminated composites.

Simulation Procedure

- Computational simulation of progressive fracture includes a large number of incremental-iterative piecewise linear analysis cycles.
- Each cycle in the simulation process begins with the definition of constituent properties from a materials databank.
- The composite mechanics module is called before and after each finite element analysis. Prior to each finite element analysis, the composite mechanics module computes the composite properties from the fiber and matrix constituent characteristics and the composite layup.
- The finite element analysis module accepts the composite properties that are computed by the composite mechanics code at each node and performs the global structural analysis iterations at each load increment.

Damage Tracking

- After a finite element analysis, the computed generalized nodal force and moment time histories are supplied to the composite analysis module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate.
- The evaluation of local damage due to fatigue loading is based on simplified mathematical models embedded in the composite mechanics module.
- The fundamental assumptions in the development of these models are the following: (1) Fatigue degrades all ply strengths at approximately the same rate (Chamis and Sinclair, 1982). (2) Fatigue degradation may be due to: (a) radiation, (b) mechanical (tension, compression, shear, and bending); (c) thermal (elevated to room temperature); and combinations (radiation, mechanical, and thermal) of loads.

Multi Factor Interaction Model (MFIM)

- **Influences of different effects on structural durability can be represented by (MFIM).**

- **The fundamental premise of MFIM is that material behavior constitutes an n-dimensional space that is called Material Behavior Space (MBS) where each point represents a specific aspect of material behavior.**

- **It is reasonable to assume that MBS can be described by an assumed interpolation function.**

- **One convenient interpolation function is a polynomial of product form because mutual interactions among different factors can be represented by the overall product.**

Discretization of MBS

- **MBS is assumed to be described by the following type of multifactor interaction equation (MFIM):**

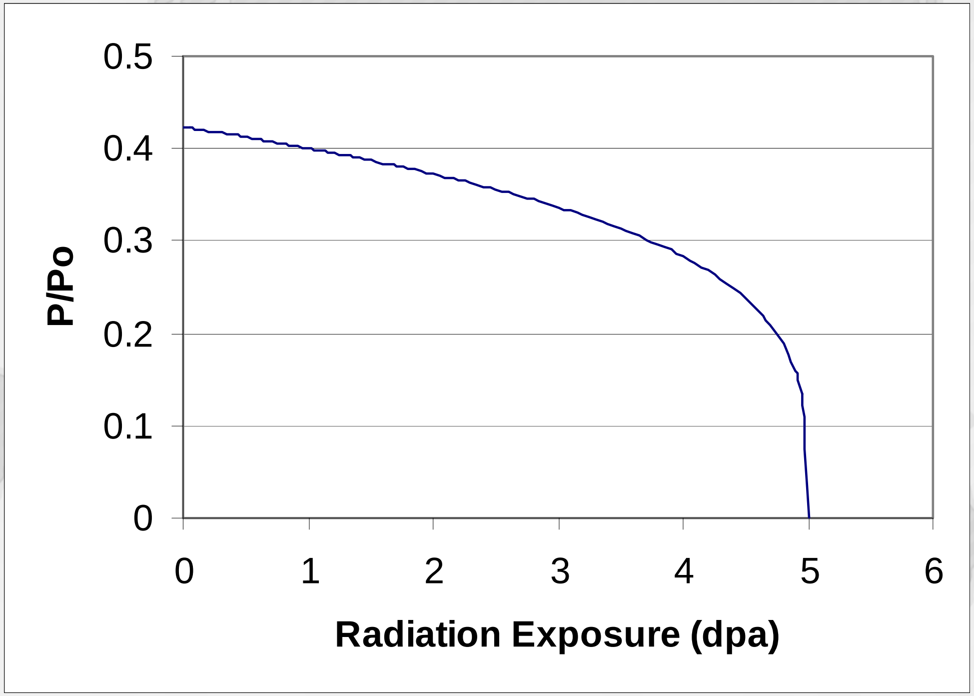
$$\frac{P}{P_o} = \prod_{i=1}^{N} \left(1 - \frac{B}{B_o}\right)_i^{m_i}$$

- **Where *P* is the property affected that is to be evaluated. P_o corresponds to the initial (reference) material state or condition. *B* represents a specific cause factor for behavior (for example, stress, temperature, radiation, etc), and B_o is the corresponding final value.**
- **Values for B_o and m_i for specific behavior are selected either from known behavior or more likely from a best judgment in conjunction with consultations with seasoned professionals for that behavior.**

MFIM MODEL FOR SiC-S/SiC COMPOSITE SUBJECT TO TEMPERATURE, STRESS, AND RADIATION

$$\frac{P}{P_o} = \left(\frac{t_{gw} - t}{t_{gw} - t_o}\right)^{mt} \left(1 - \frac{\sigma}{S}\right)^{ms} \left(1 - \frac{\sigma R}{S.R_f}\right)^{mr}$$

t_{gw}=1,700°C,
t_o=25°C, σ/S=0.4,
R_f=5 displacements per atom (dpa),
mt=0.5, ms=0.5,
mr=0.25



Effect of Radiation on Property Degradation for T=1,200°C and σ/S=0.4.

RADIATION FATIGUE BEHAVIOR SIMULATION OF SiC-S/SiC CMC STRUCTURE

$$\frac{P}{P_o} = \left(\frac{t_{gw} - t}{t_{gw} - t_o}\right)^{mt} \left(1 - \frac{\sigma}{S}\right)^{ms} \left(1 - \frac{\sigma R}{S.R_f}\right)^{mr}$$

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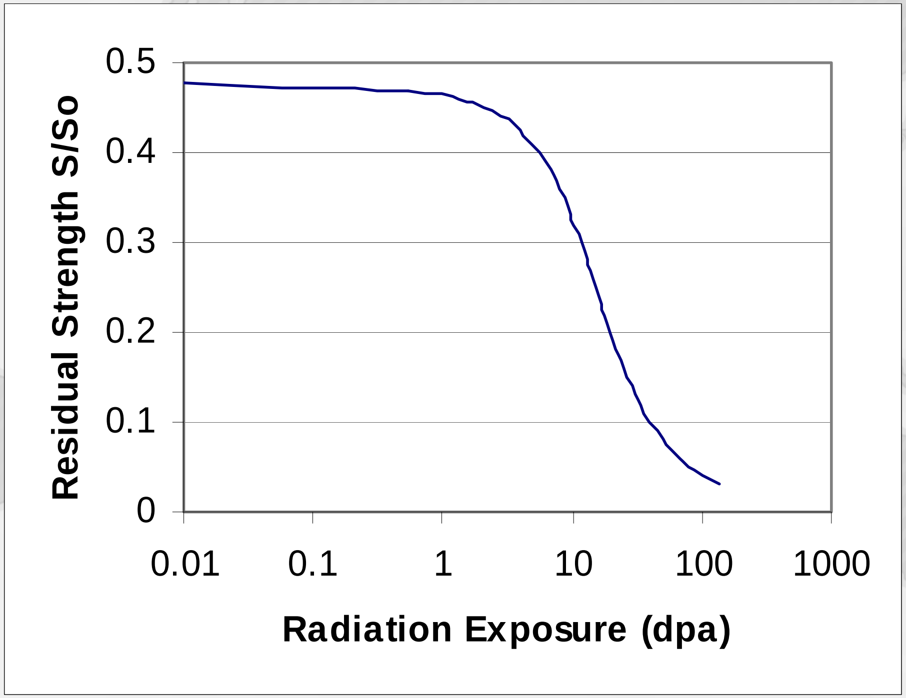


Effect of Radiation Exposure on Residual Strength Ratio for T=1,200°C and σ/S=0.4.

SiC-S Fiber Properties:

Number of fibers per end = 5000

Fiber diameter = 0.012 mm (4.724E-4 in)

Fiber Density = 7.182E-7 Kg/m^3 (0.112 lb/in^3)

Longitudinal normal modulus = 420 GPa (60.92E+6 psi)

Transverse normal modulus = 14.7 GPa (2.13E+6 psi)

Poisson's ratio (ν_{12}) = 0.320

Poisson's ratio (ν_{23}) = 0.355

Shear modulus (G_{12}) = 24.84 GPa (3.60E+6 psi)

Shear modulus (G_{23}) = 11.04 GPa (1.60E+6 psi)

Longitudinal thermal expansion coefficient = 3.8E-6/°C (2.11E-6 /°F)

Transverse thermal expansion coefficient = 3.8E-5/°C (2.11E-6 /°F)

Longitudinal heat conductivity = 0.3016 J-m/hr/m^2/°C (4.03 BTU-in/hr/in^2/°F)

Transverse heat conductivity = 0.03016 J-m/hr/m^2/°C (0.403 BTU-in/hr/in^2/°F)

Heat capacity = 0.712 KJ/Kg/°C (0.17 BTU/lb/°F)

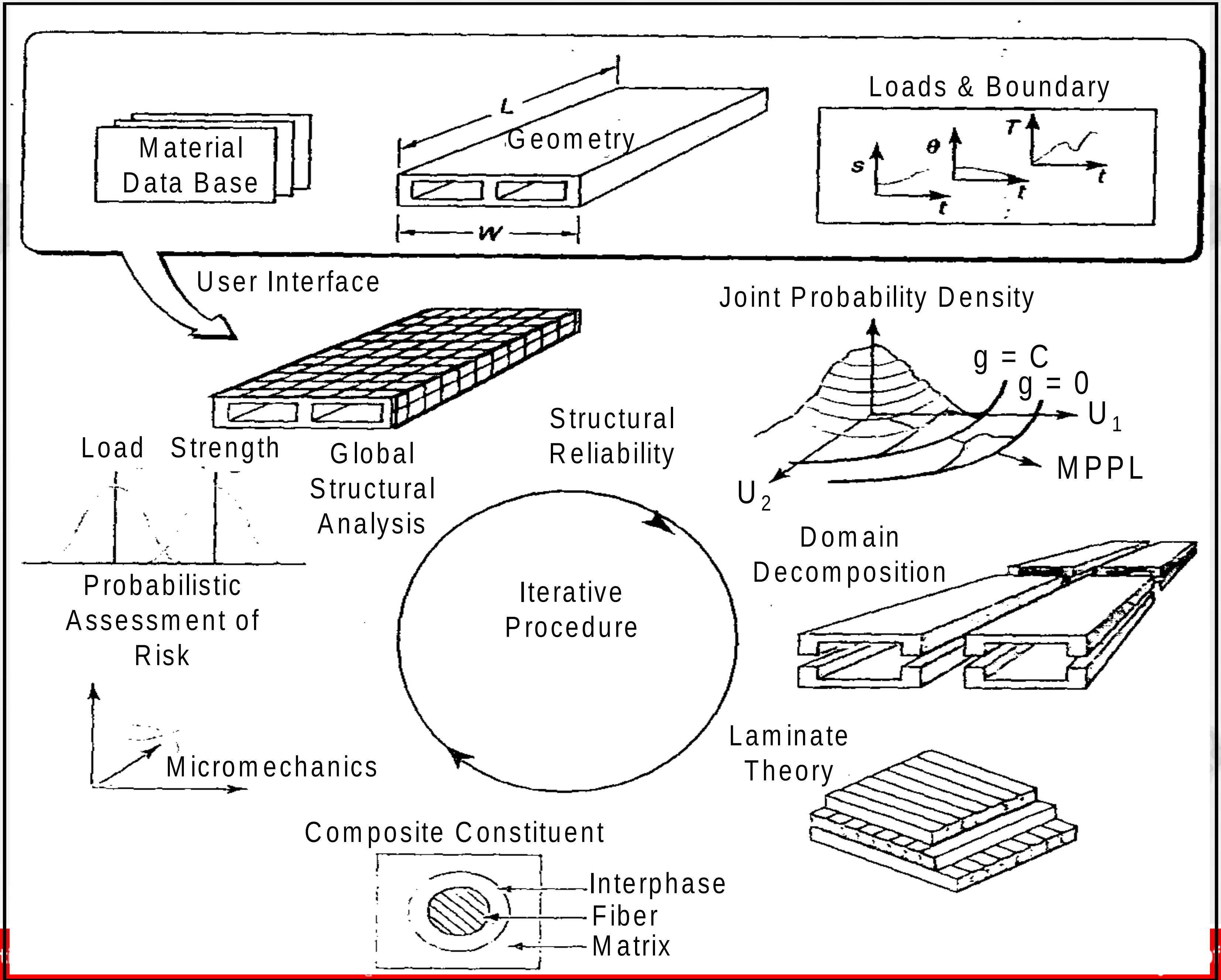
Tensile strength = 1.379 GPa (200 ksi)

Compressive strength = 1.379 GPa (200 ksi)

SiC Matrix Properties:

Matrix density = 8.324E-7 Kg/m^3 (0.112 lb/in^3)
Normal modulus = 419.5 GPa (60.92 Msi)
Poisson's ratio = 0.32
Coefficient of thermal expansion = 3.80E-6/°C (2.111E-6 /°F)
Heat conductivity = 0.654E-3 J-m/hr/m^2/°C (0.868E-8 BTU-in/hr/in^2/°F)
Heat capacity = 1.047 KJ/Kg/°C (0.25 BTU/lb/°F)
Tensile strength = 93.73 MPa (13.1 ksi)
Compressive strength = 283 MPa (41.0 ksi)
Shear strength = 138 MPa (20.0 ksi)
Allowable tensile strain = 0.02
Allowable compressive strain = 0.05
Allowable shear strain = 0.04
Allowable torsional strain = 0.04
Void conductivity = 16.8 J-m/hr/m^2/°C (0.225 BTU-in/hr/in^2/°F)
Melting temperature = 1700°C (3092°F)

Sources of Uncertainties in Composite Structures



Design Variables with Uncertainties

- Fiber Tensile Strength
- Fiber Compressive Strength
- Matrix Tensile Strength
- Matrix Shear Strength
- Matrix Modulus of Elasticity
- Ply Thickness
- Normal Probability Distributions

Response Variables Evaluated

- Number of Hours to Failure
- Percent Damage at Failure
- Damage Energy Exhausted at Failure

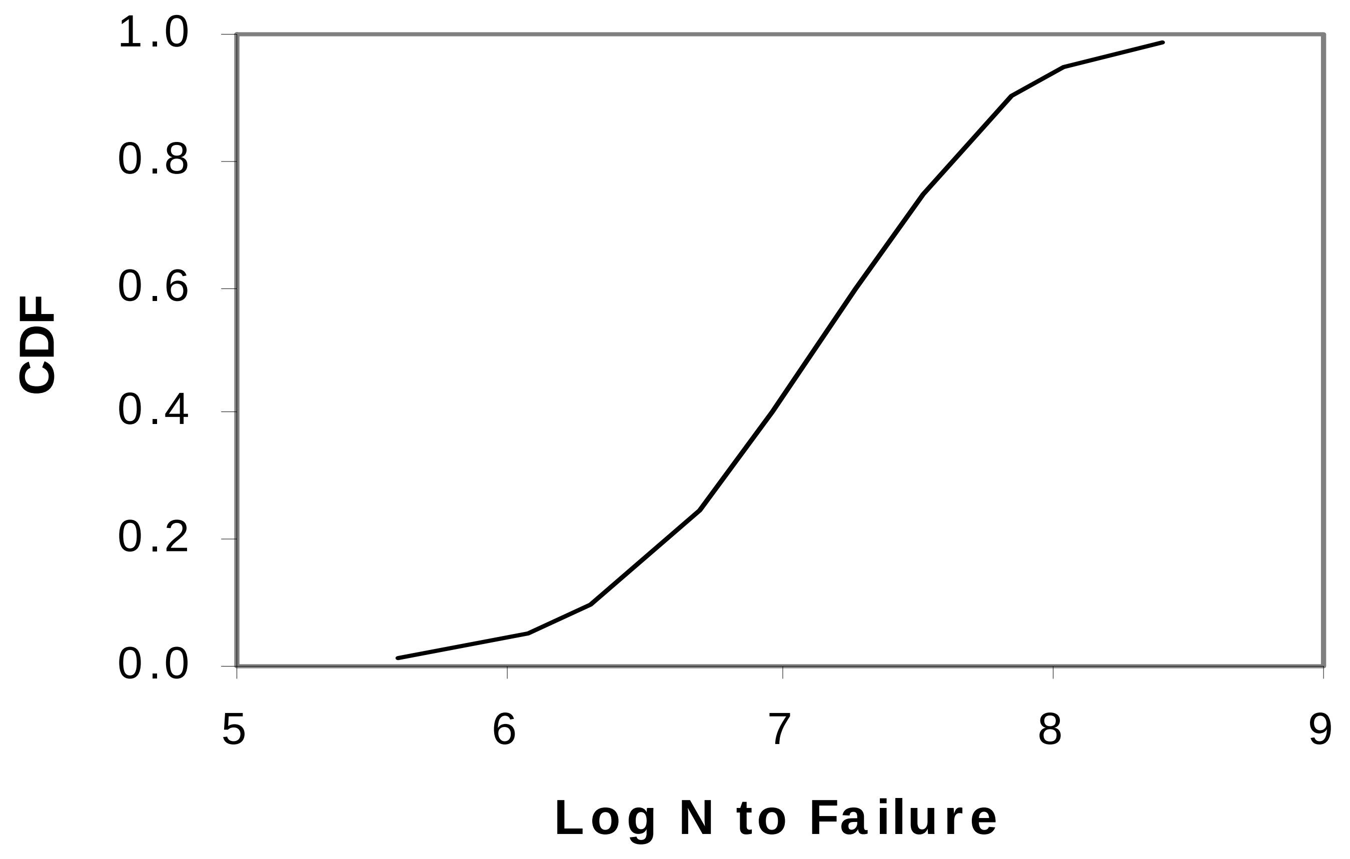
Integrated Probabilistic Structural Fracture Simulation Features

- Composite micromechanics and macromechanics
- Local damage criteria under radiation exposure
- Progressive damage and fracture simulation
- 2-D and 3-D fiber reinforcement patterns
- Damage evolution and damage tolerance characteristics
- Probabilistically defined material, fabrication, and structural variables.
- Effects of design variable uncertainties on structural response and structural durability quantified.
- Sensitivities of structural durability to random variables identified.

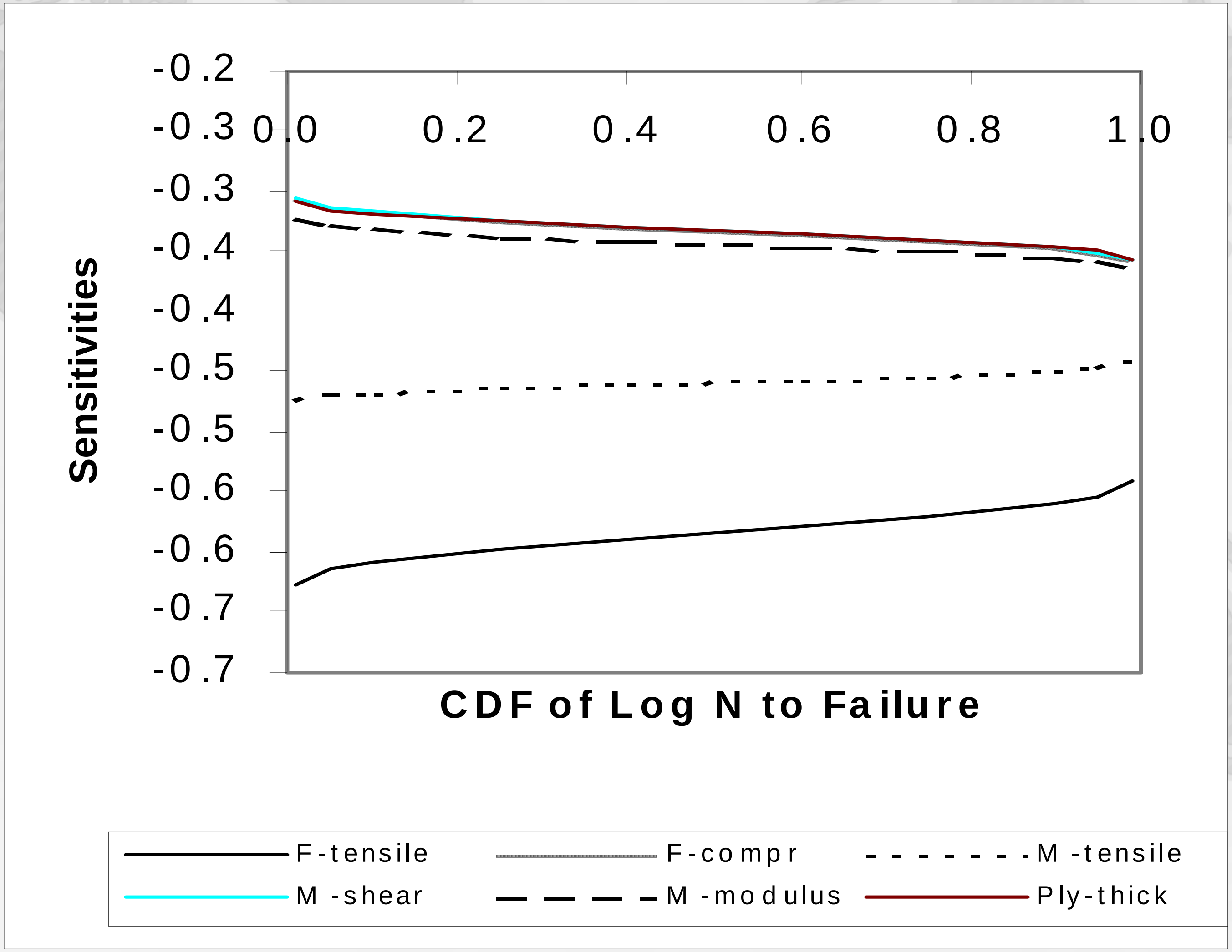
Integrated Probabilistic Structural Fracture Simulation Features

- The probabilistic analysis considers the uncertainties in material properties as well as in the composite fabrication process.
- The effects of uncertainties in all the relevant design variables on the durability and damage tolerance of the structure are quantified.
- Cumulative distribution functions (CDF) are obtained for the structure response.
- Sensitivities of various design variables to structure response are also obtained.
- Input data for probabilistic analysis is generated from the degrading composite model available as progressive damage and fracture stages are monitored.

CDF of Number of Hours N to Failure



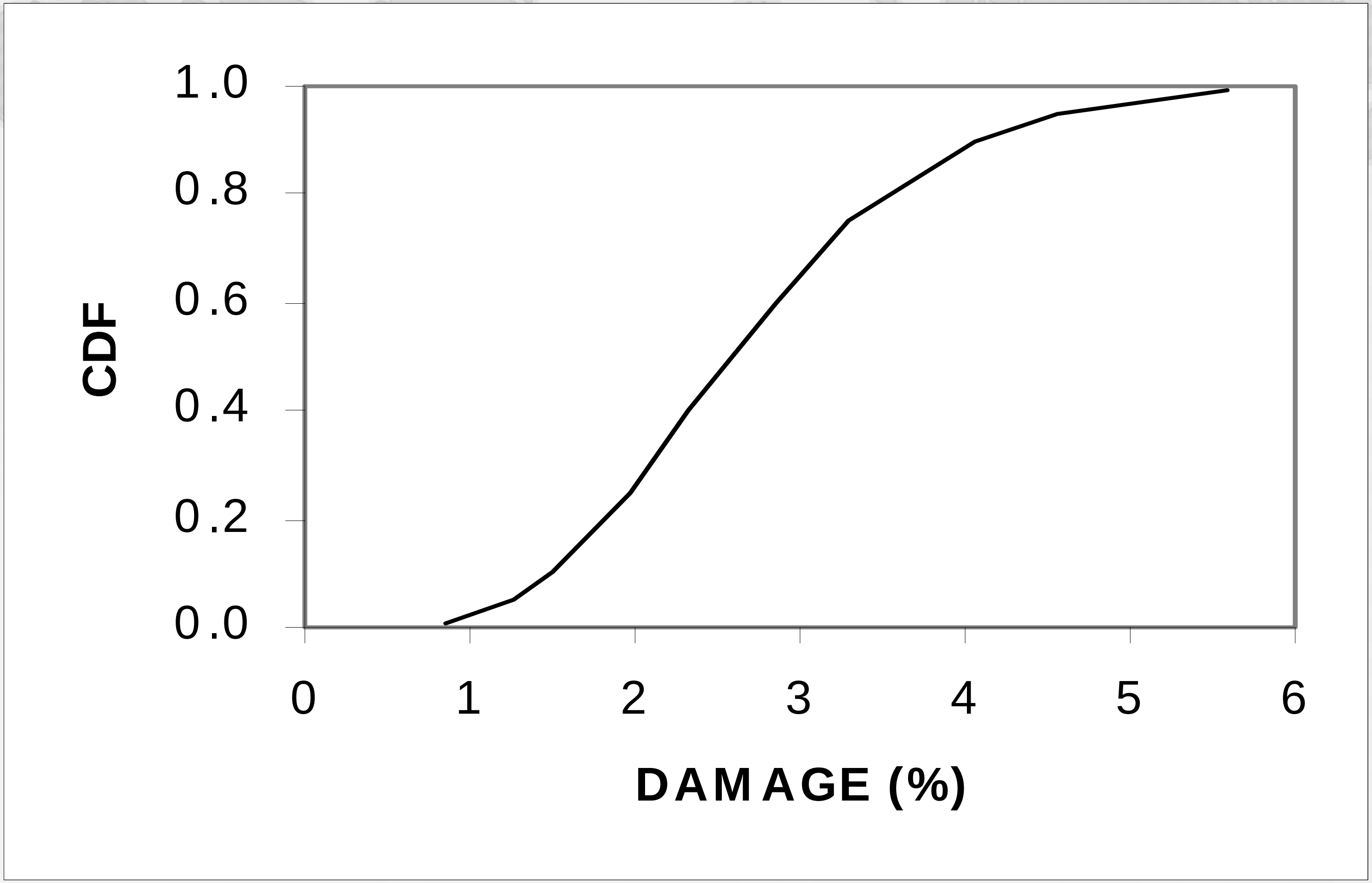
Sensitivity of Number or Hours N to Failure to Primitive Design Variables



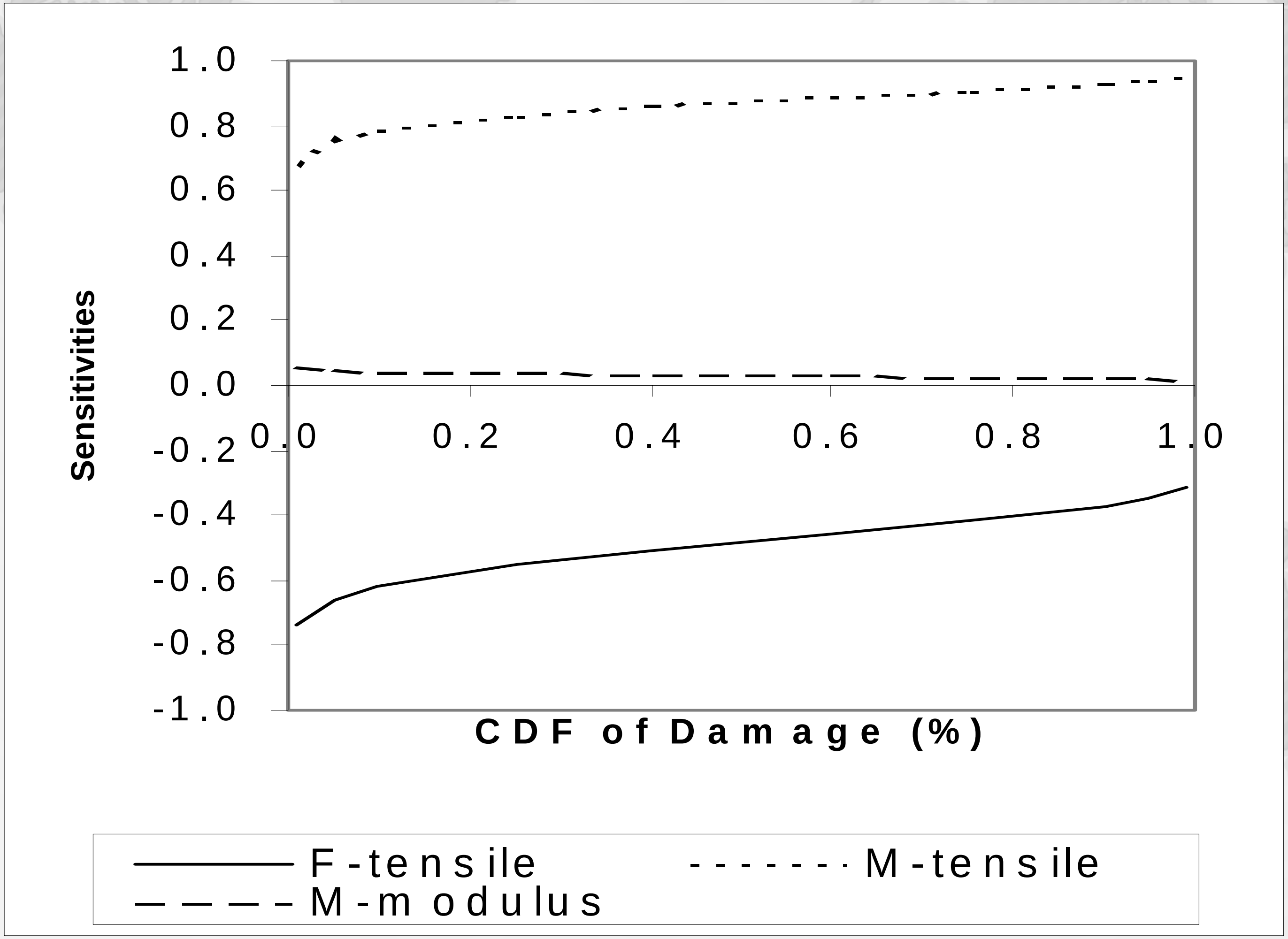
Effect of Probability Level on Sensitivities

- **The number of hours to failure is most sensitive to the fiber tensile strength for all probability levels.**
- **At high probability levels, the sensitivity to fiber and matrix tensile strength decreases and sensitivity to other design variables increases.**
- **If the design point is to be limited to very low probability of failure then reducing the uncertainty of fiber tensile strength is the most important design concern.**
- **At high probability levels as the composite endures a significant amount of damage, other variables such as fiber compressive strength, matrix shear strength, matrix modulus and ply thickness gain more influence in determining the number of hours to failure.**

CDF of Percent Mechanical Damage Volume at Failure



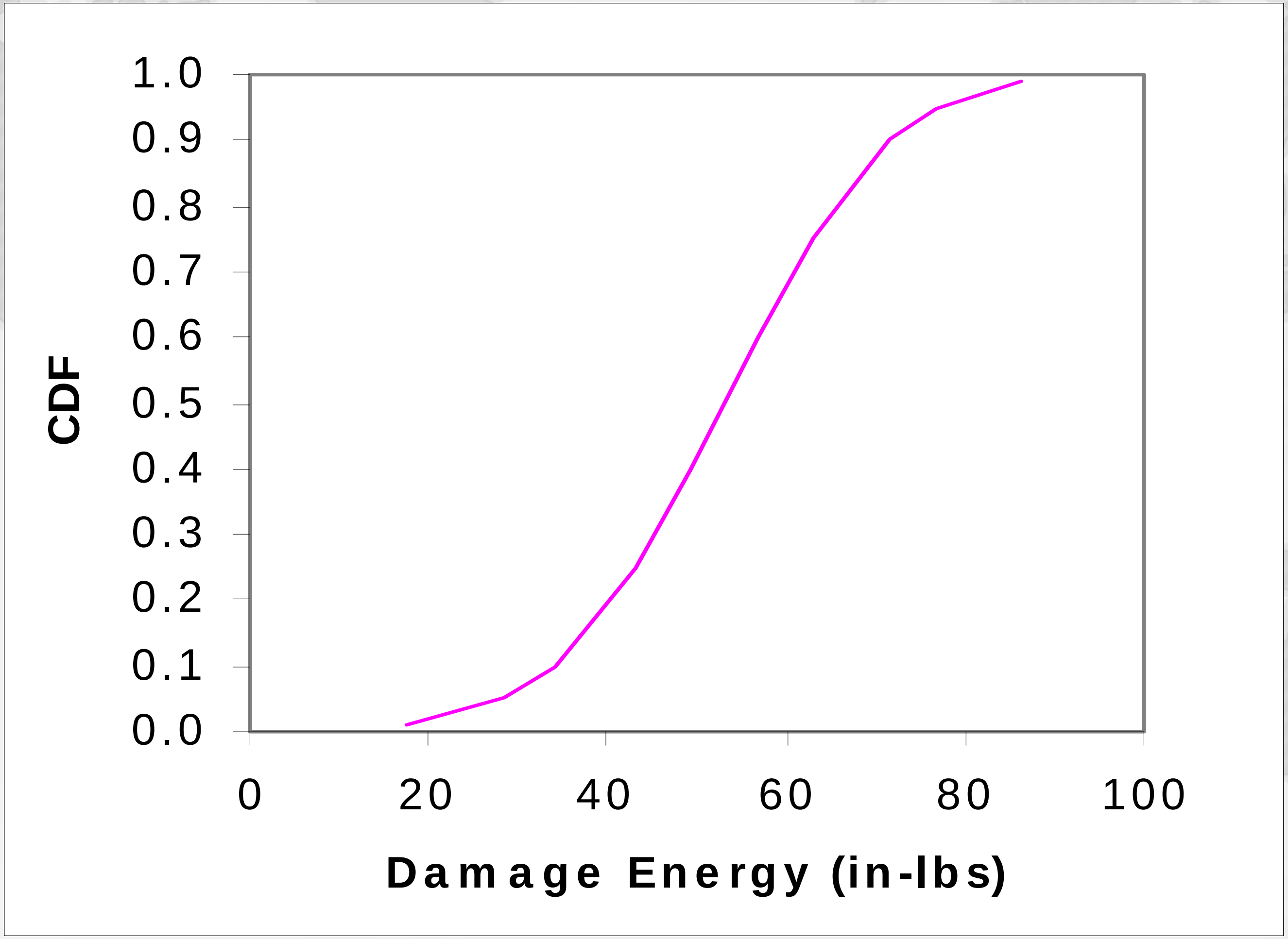
Sensitivities of Damage at Failure to Design Variables



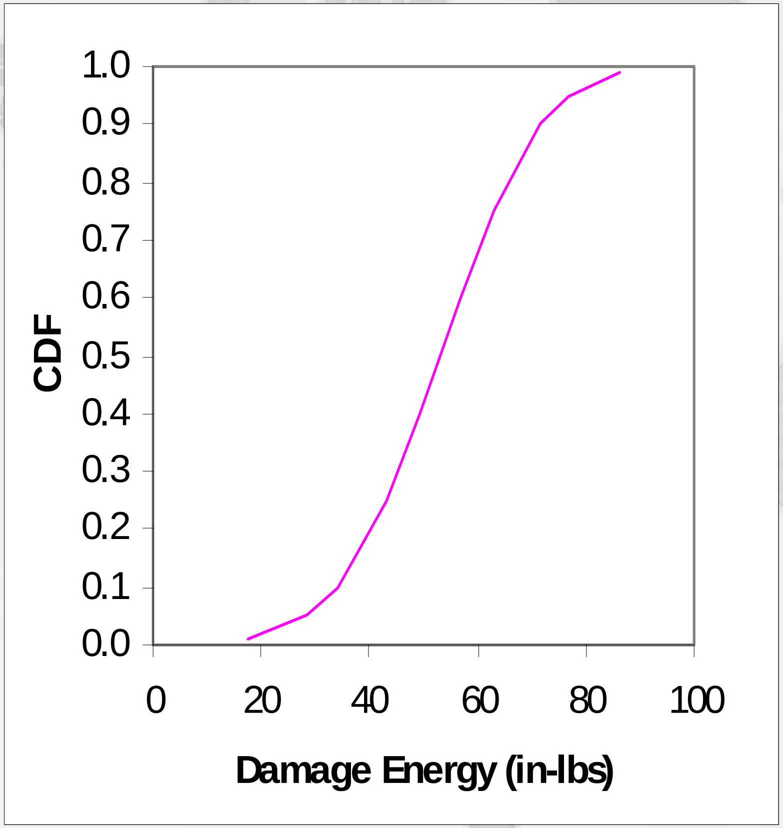
Sensitivities of Damage Volume to Primitive Design Variables

- The damage volume at failure is most sensitive to the fiber tensile strength at low probabilities.
- At high probabilities the matrix tensile strength becomes much more influential.
- The damage volume has less sensitivity to matrix modulus.
- The remaining primitive variables have very little influence on the damage volume at failure.

CDF of Damage Energy Exhausted at Failure

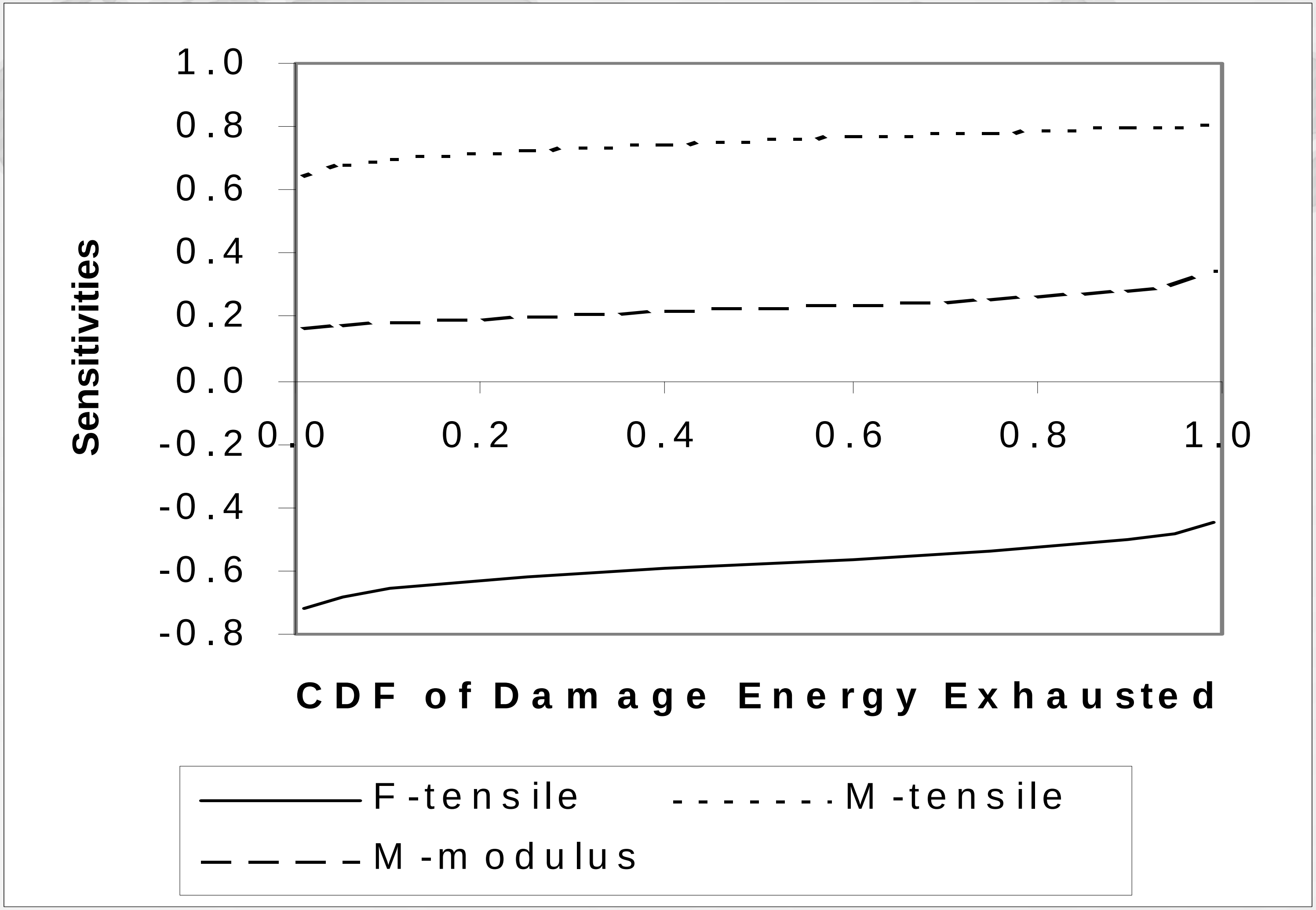


Effect of Probability Level on Exhausted Damage Energy

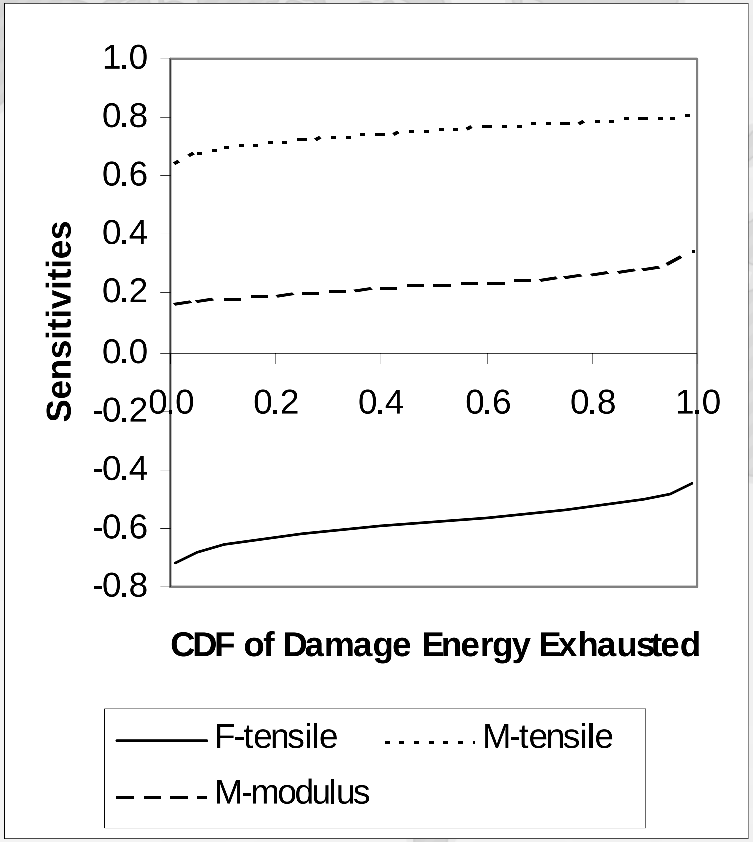


- The exhausted damage energy values are lower at low probability levels indicating the localization of fracture propagation.
- At high probability levels the exhausted damage energy is increased indicating widespread structural damage propagation.

Sensitivities of Exhausted Energy to Primitive Design Variables



Sensitivities of Exhausted Damage Energy



- The sensitivity of exhausted damage energy to primitive design variables is similar to that of damage volume, as may be expected.
- The design implication is that if the uncertainties in the fiber tensile strength were reduced, the number of hours to failure would increase and the ability of the composite structure to resist fracture propagation would become more dependent on the matrix tensile strength.

Summary

- The CDF for the number of hours N to failure shows that at high probabilities, N is three orders of magnitude higher than that at low probabilities
- The number of hours to failure N is most sensitive to fiber tensile strength and second to matrix tensile strength
- The percent damage volume and the damage energy exhausted at failure are most sensitive to fiber tensile strength at low probabilities and to matrix tensile strength at high probabilities
- At low probabilities the percent damage and damage energy exhausted at failure are low due to localization of the fracture path
- At high probabilities damage levels are high due to the evolution of distributed damage patterns without critical failures

Conclusions

- Methods and corresponding computer codes were discussed for probabilistically assessing the time to failure under loading at elevated temperatures in a radiation environment.
- The presented approach integrates composite mechanics with MFIM (for composite behavior) with finite element analysis (for global structural response) and incorporates probability algorithms to perform a probabilistic assessment of composite structural fracture.
- The effect on the composite structural damage of the design variable uncertainties was accounted for at all composite scales.
- Probabilistic scatter range and sensitivity factors are key results obtained from the probabilistic assessment of composite structures subject to fracture.
- The sensitivity factors provide quantifiable information on the relative sensitivity of structural design variables on the respective structure response.