APPLICATION OF NON-DETERMINISTIC METHODS TO ASSESS MODELLING UNCERTAINTIES FOR REINFORCED CARBON-CARBON DEBRIS IMPACTS

K. Lyle
NASA Langley Research Center, Hampton VA

E. Fasanella
ARL-VTD Langley Research Center, Hampton VA

M. Melis and K. Carney
NASA Glenn Research Center, Cleveland OH

J. Gabrys
The Boeing Company, Philadelphia PA

Abstract

The Space Shuttle Columbia Accident Investigation Board (CAIB) made several recommendations for improving the NASA Space Shuttle Program. An extensive experimental and analytical program has been developed to address two recommendations related to structural impact analysis. The objective of the present work is to demonstrate the application of probabilistic analysis to assess the effect of uncertainties on debris impacts on Space Shuttle Reinforced Carbon-Carbon (RCC) panels. The probabilistic analysis is used to identify the material modeling parameters controlling the uncertainty. A comparison of the finite element results with limited experimental data provided confidence that the simulations were adequately representing the global response of the material. Five input parameters were identified as significantly controlling the response.

Introduction

The Space Shuttle Columbia Accident Investigation Board (CAIB) made several recommendations for improving the NASA Space Shuttle Program in Volume I of the final report, Ref. [1]. Two recommendations directly related to structural impact analysis are:

- *Initiate a program designed to increase the Orbiter's ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes.*
- *Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive corrective action, such as on-orbit inspection and repair, when indicated.*

An extensive experimental and analytical program has been developed to address these recommendations. Specifically, a multi-center analysis team has been formed to: 1) use physics-based state-of-the-art codes to simulate debris impacting the Shuttle Thermal Protection System (TPS); 2) validate modelling approaches through test-analysis correlation; and 3) utilize validated modelling approaches to assist in investigating issues not possible to test, (e.g., performing parameter studies, simulating additional scenarios, and establishing worst case scenarios). An overview of the team's activities to date is documented in Ref. [2]. Related large-scale simulations are presented in Refs. [3, 4].

The NASA Space Shuttle leading edge is fabricated from reinforced carbon-carbon (RCC) material. The fabrication process is very complex, and the details are provided in Ref. [5]. To begin fabrication, a precursor woven fabric is layered such that all plies are either in the 0 or 90 degree direction. During the processing, silica is infused in the outer 2-to-3 laminae, and the resulting laminate is heated to form a silicon-carbide coating, see Figure 1. This silicon-carbide coating is necessary to provide protection to the Space Shuttle's leading edge during the high heating experienced on re-entry of the shuttle through the Earth's atmosphere. As shown in Figure 1, the RCC laminate contains many voids. In addition, the process used to create the silicon-carbide causes numerous micro-cracks in the silicon-carbide coating. The porosity and the coating cracks result in a material with a highly complex stress-strain and failure behavior.

An extensive test program begun in the 1970's generated data used to design the TPS. This information was revised and published in Ref. [6]. As part of the shuttle design process, several tests were performed to establish the effective material properties of the RCC laminate material. The effective laminate properties are dependent on several factors including whether the material is as-fabricated or has a degraded strength due to mass-loss heating. The data are also affected by the relative thickness of the silicon-carbide coating and the carbon-carbon substrate.

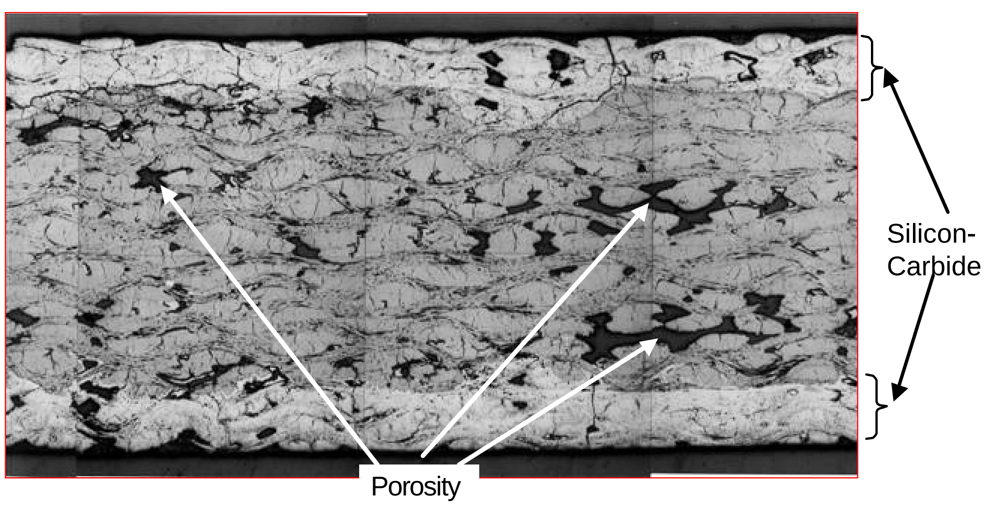

Figure 1. Micro-graph cross-section of 19-ply RCC material.

The objective of the present work is to demonstrate the application of probabilistic analysis to assess the effect of various uncertainties on debris impacts on Space Shuttle RCC panels. For general impact dynamics applications, factors affecting modeling and experimental uncertainty include: off-nominal impact conditions (e.g., attitude and velocity); material property variations (e.g., stress-strain relationships, failure modes, rate dependencies); and fabrication anomalies (e.g., non-uniform cross-sections, imperfect structural assembly). Many papers concerning probabilistic analysis for aerospace applications exist in the literature, for example see Refs [7,8]. Although extensive work has been done to enable the use of probabilistic analysis, few applications involve impact dynamics of aerospace structures. Preliminary work utilizing probabilistic analysis to bound modeling uncertainty and design optimization for aircraft crashworthiness has been documented in Refs. [9,10].

Historical data has shown that RCC material is somewhat brittle and that the stress-strain relationship is uncertain. Therefore, probabilistic analysis will be used to identify the material modeling parameters controlling the response uncertainty. For the purposes of this demonstration, the simulations replicate beam testing performed in support of the Columbia Accident Investigation. The results for the simple model presented here can provide insight for assessing the uncertainty for more complex structures, such as the space shuttle wing leading-edge panels.

Description of Experiment

Virtually no data existed concerning the response of RCC material to a foam impact. Thus, tests were performed to provide preliminary data about the response of RCC panels to impacts by external tank foam. The tests were performed at NASA Glenn Research Center at the Ballistic Test Facility. A photograph of the test set-up is shown in Figure 2. Details about the operation of the facility can be found in Ref. [11]. For these tests, cylindrical foam projectiles impacted 1.5-in x 6-in., 19-ply RCC beam specimens at velocities ranging from 397 to 695 ft/s. The beams were simply-supported 0.5-in. from each end. The foam projectile was 1.25-in. in diameter and 3-in. long. Beam deflections and constraint loads were measured and recorded at a 50 kHz sample rate.

The intent of the paper is to understand the uncertainty at the threshold of damage and to determine the parameters controlling the uncertainty. For this reason, the paper will focus on the 555 ft/s impact velocity case. A series of images taken from the high-speed video camera is shown in Figure 3. Post-test examination of the test article showed a partial crack through the thickness.

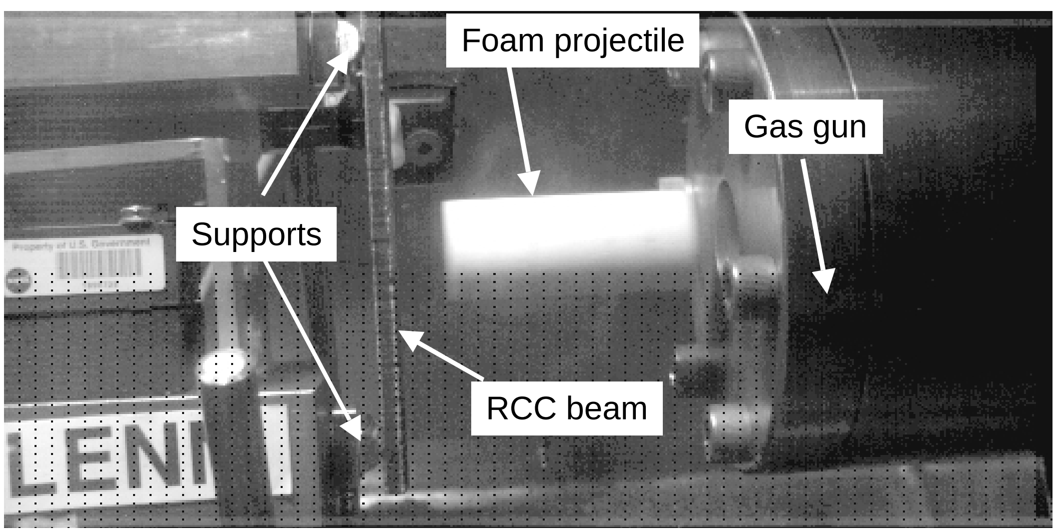

Figure 2. Photograph of beam test set-up just prior to foam impact.

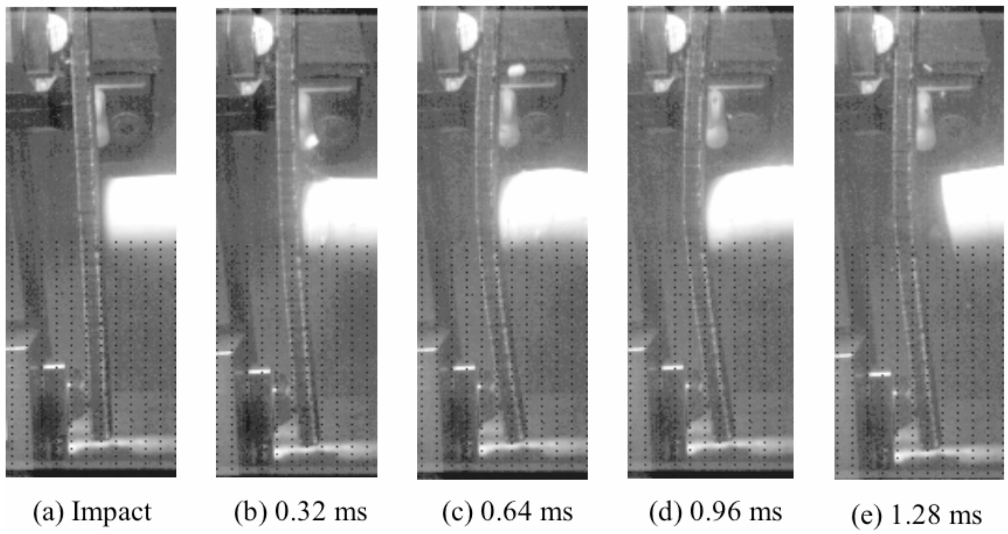

Figure 3. Series of photographs showing panel impacted by foam cylinder.

Description of Finite Element Model

To make this study possible, the finite element model was developed with three requirements in mind. The model and simulations must be computationally efficient, stable, and capable of capturing the basic physics of the desired structural response. Computational efficiency is necessary to enable completion of the numerous simulations. The simulations must be stable over the span of input parameters to avoid non-physical or non-feasible responses. Finally, the simulations must capture the basic physics concerning the RCC response to impact loading near the threshold of damage.

The finite element model is shown in Figure 4. The RCC beam coupon is represented by 900 shell elements with an edge length of 0.1 in. The external tank foam is represented by 5,250 solid elements. The material property of the foam has been implemented in LS-DYNA, Ref. [12], using MAT # 83 (MAT_FU_CHANG_FOAM). The RCC beam is simply-supported 0.5-in. from the ends to replicate the test condition. The RCC material model has been implemented using MAT # 58 (MAT_LAMINATED_COMPOSITE_FABRIC). Information about the development of the material models can be found in Ref. [13]. Each 1.5-millisecond simulation required about 7 minutes CPU on an HP 4000 Linux workstation.

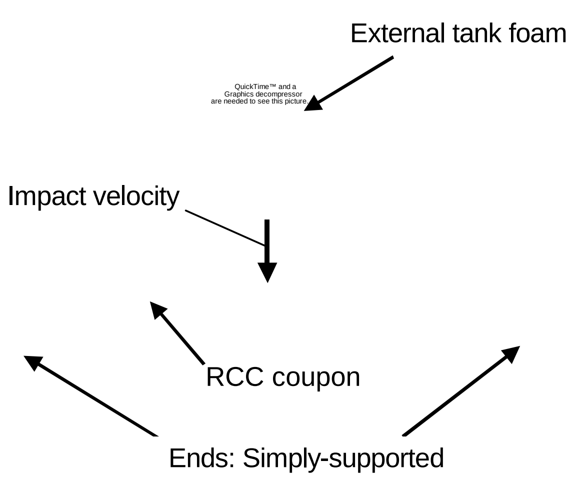

Figure 4. Finite element model.

Description of Probabilistic Analysis

A probabilistic analysis approach was used to approximate the uncertainty inherent in the modeling and simulation of a highly nonlinear structural impact. For this application, the uncertainties are related to the material modeling parameters used in the LS-DYNA Mat # 58 (MAT_LAMINATED_COMPOSITE_FABRIC).

A schematic of the probabilistic analysis approach is shown in Figure 5. The approach utilizes two commercial codes – Matlab, Ref. [14] and LS-DYNA. Matlab scripts control the input parameters and the LS-DYNA executions. Following each LS-DYNA simulation, the input parameters as well as the pertinent results, such as material energies, nodal displacements, global model statistics, screen output, etc., are stored. These results are extensively reviewed prior to conducting the probabilistic analysis to identify anomalies. The current probabilistic analysis employs 500 Monte Carlo simulations. Five hundred Monte Carlo simulations were sufficient to identify the parameters controlling the response variability. All post-processing was conducted with user-written Matlab scripts.

Several aspects were considered when selecting the parameters to vary as well as the numerical distribution for each parameter, see Table I. Minimal information about the distributions for the input parameters was available. Ten of the twelve parameters were assumed to have normal distributions with a mean determined from the average strength, as-fabricated information given in Ref. [6]. The standard deviation was computed based on the recent testing performed on RCC fragments from the Southwest Research Institute field tests, Ref. [1], where applicable. Two failure parameters in Table I, $\mathbf{S_T}$ and $\boldsymbol{\varepsilon_{fail}}$, account for additional material behaviors not adequately described with the data typically acquired from material characterization. These two parameters were assigned uniform distributions with the mean and standard deviation based on engineering judgment. Since these parameters become important at the damage threshold, they were considered relevant to include in this study. The probabilistic analysis was performed in standard normal space, i.e., the mean is 0 and the standard deviation is 1. The coefficients of variation, based on the values used as input to LS-DYNA, have been included in the table.

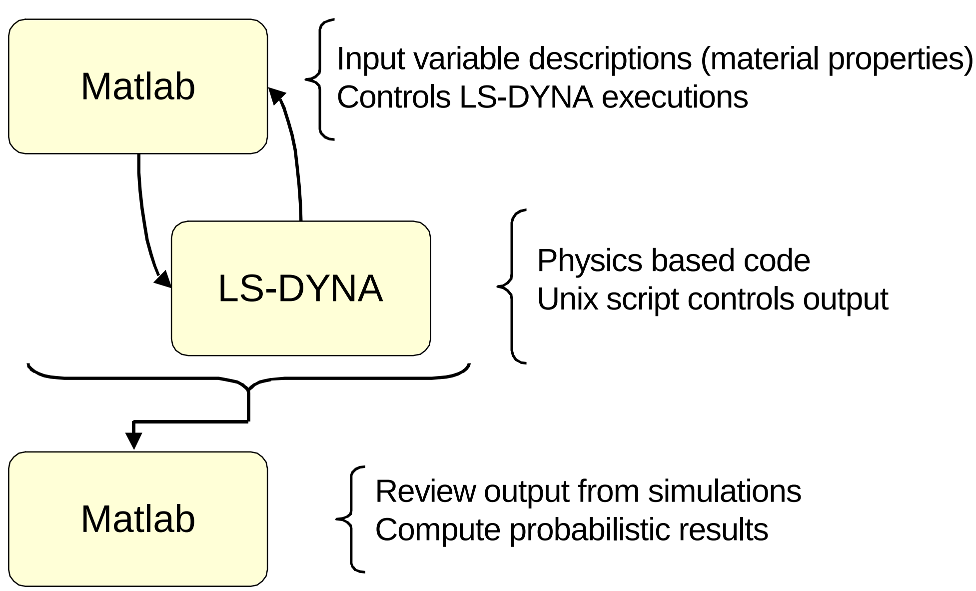

Figure 5. Schematic of probabilistic analysis.

Table I. Description of input parameters.

Symbol	LS-DYNA parameter	Description	Coefficient of variation
ρ	RHO	Density	0.0258
E	EA & EB & EC	Young's modulus	0.0222
ν	PRBA	Poisson's ratio	0.0435
G	GAB & GBC & GCA	Shear modulus	0.18
$\mathbf{S_T}$	SLIMT1 & SLIMT2	Min. tensile stress limit	0.072
ε_{fail}	ERODS	Max. eff. strain for layer failure	0.173
ε_C	E11C & E22C	Max. compressive strain	0.05
ε_T	E11T & E22T	Max. tensile strain	0.14
ε_{sh}	GMS	Max shear strain	0.05
σ_C	XC & YC	Max compressive stress	0.0343
σ_T	XT & YT	Max tensile stress	0.11
σ_{sh}	SC	Max shear stress	0.05

Discussion of Results

The center displacement time histories (non-dimensionalized) for the 500 simulations and the measurements are shown in Figure 6. Center displacements were selected for comparison because: 1) they provide a global measure of the beam response; 2) they are easily computed in the analytical simulations; and 3) they are frequently used to evaluate the accuracy of finite element simulations. As expected when computing near the threshold of damage for a fairly brittle material, a large variation in response is apparent. Two distinct response classes (denoted A and B in Figure 6) are evident. For Class A, the damage is not sufficient to prevent the beam from rebounding. However for Class B, extensive damage within the center elements creates a significantly weakened area with little resistance to additional deformations.

The measured displacement (solid line) falls within the predicted range. This indicates that good agreement between test and analysis was achieved when accounting for documented uncertainty in the material behavior.

Additional structural responses can be examined analytically for which test data is not available. The beam internal energy, Figure 7, and the contact force, Figure 8, are two examples. The beam internal energy was selected for evaluation because it corresponds to the strain energy. Similar to the center displacements, two distinct internal energy classes are apparent in Figure 7. A review of the input parameter statistics (mean and standard deviation) shows that two input parameters, $\mathbf{S_T}$ and $\boldsymbol{\sigma_T}$, are most likely responsible for the two distinct energy classes. On the other hand, the contact force exhibits much less variation. The contact force when integrated over time yields the change in momentum.

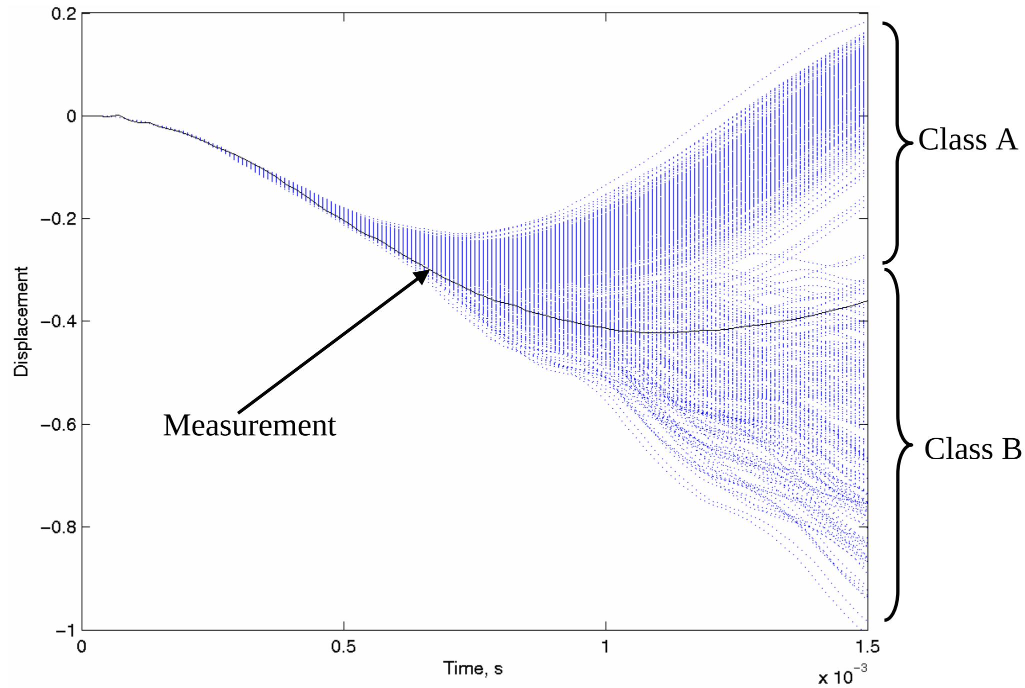

Figure 6. Measured and predicted center displacements (non-dimensional) for 555 ft/s impact.

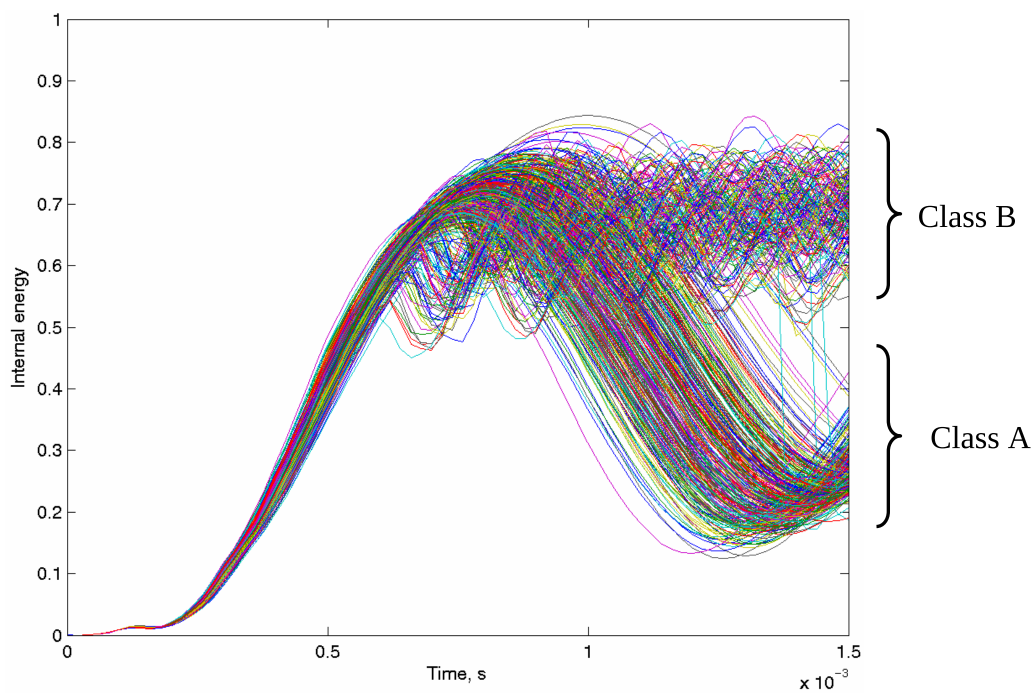

Figure 7. Beam internal energy (non-dimensional) for 500 Monte Carlo simulations.

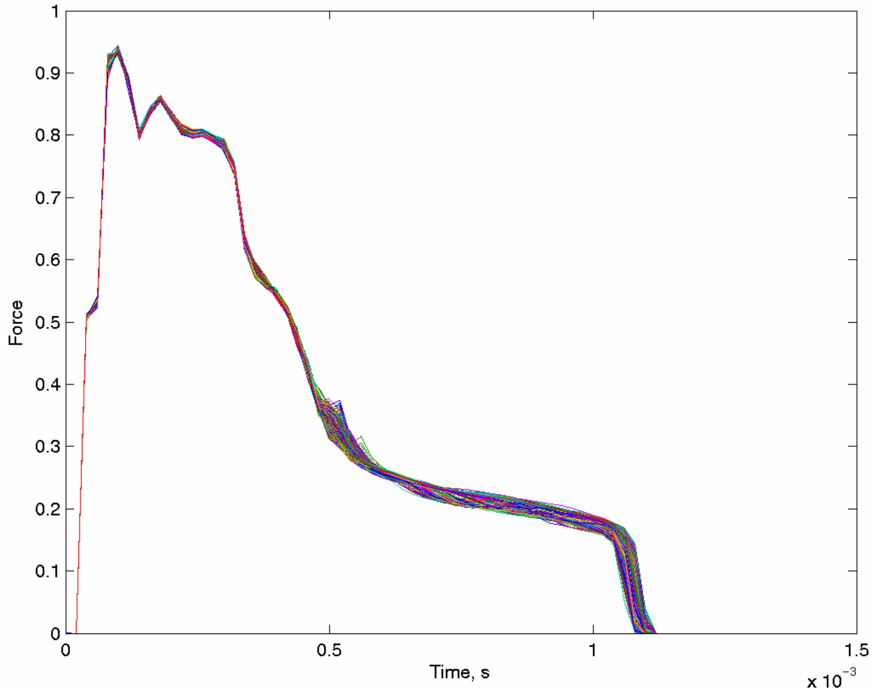

Figure 8. Contact force (non-dimensional) for 500 Monte Carlo simulations.

To aid in the process of determining the sources of material modeling uncertainty, a sensitivity analysis was performed. Three outputs were selected to assess the sensitivity of the beam response to material modeling uncertainty: the maximum center displacement, the maximum internal energy, and the change in momentum (integration of contact force over time). A 2^{nd}-order polynomial response surface was fit to the 500 Monte Carlo simulations using a regression analysis. This response surface polynomial captures variations in responses (displacement, internal energy, momentum) due to changes in material properties. Earlier analyses showed little difference when a 2^{nd}-order polynomial was compared to a 4^{th}-order polynomial. Three response surface approximations were generated representing the three outputs. The derivatives are computed by analytically differentiating the response surface expression and then substituting the mean value for each parameter into the algebraic expression for the derivative.

To compute the gradients, the derivatives were multiplied by the mean of the input parameter. For each parameter, the gradient was normalized by the value for the maximum tensile stress, $\boldsymbol{\sigma_T}$, see Figure 9. For all three responses, four parameters consistently show the largest gradient, ρ, **E**, $\mathbf{S_T}$, and $\boldsymbol{\sigma_T}$. The accuracy of the gradients was verified with simple check runs.

The gradient information reflects the effect of small changes about the mean. However, it does not incorporate the uncertainty for the input variable. For this reason, the derivatives were multiplied by the standard deviation to compute the sensitivity of the output to the various input parameters, see Figure 10. As for the gradients, the sensitivities have been normalized by the value for $\boldsymbol{\sigma_T}$. Similar trends are seen as for the gradients. However, the large uncertainty for $\boldsymbol{\varepsilon_{fail}}$ makes it more important, while the relatively small uncertainty for **E** decreases its importance. All three outputs show the largest sensitivity to the tensile stress limit, $\boldsymbol{\sigma_T}$.

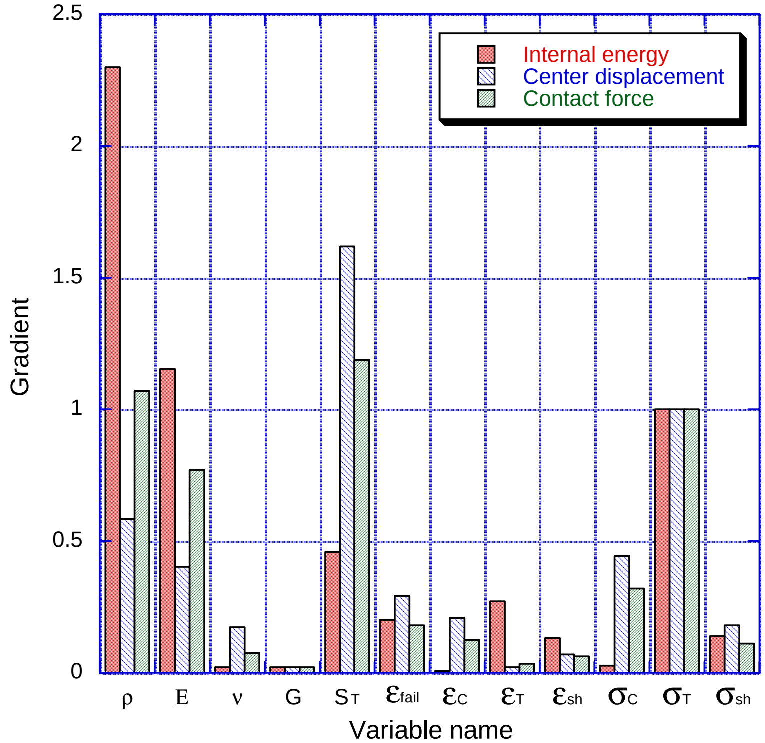

Figure 9. Normalized gradient of responses based on 500 Monte Carlo simulations.

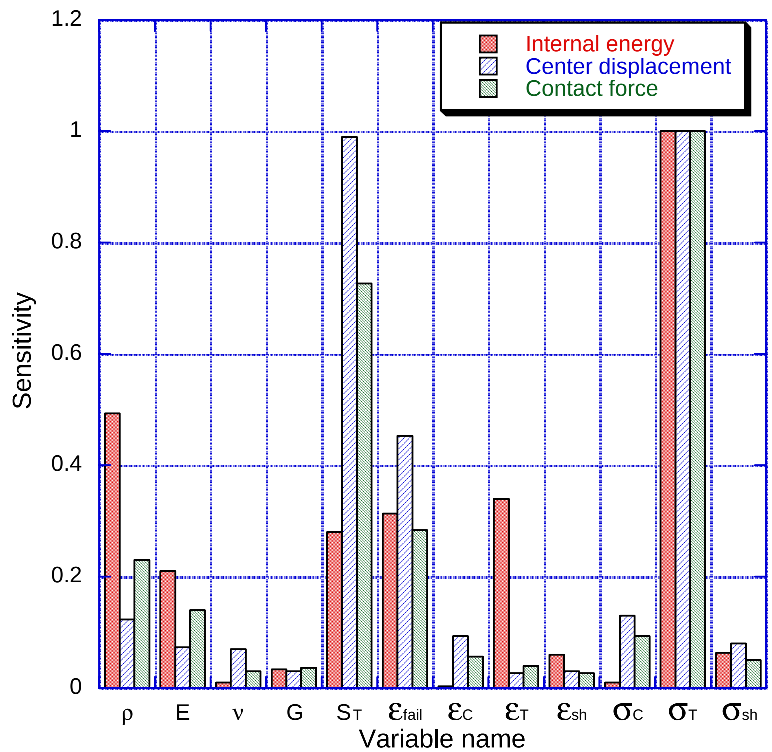

Figure 10. Normalized sensitivity of responses based on 500 Monte Carlo simulations.

The gradient and sensitivity information helps identify the variables that contribute most to the response uncertainty. This information can be used to allocate resources for future work, to improve (reduce) the uncertainty, and to better understand the effect of these uncertainties on the structural response. For example, for this application the tension data is more likely to affect the accuracy than the compression data. In addition, as would be expected, near the threshold of failure $\mathbf{S_T}$ and $\boldsymbol{\varepsilon_{fail}}$ become more important.

Concluding Remarks

An application of probabilistic analysis to compute the effect of material modeling uncertainty on the response of Space Shuttle RCC leading edge material to debris impacts has been presented. The example structure is an RCC beam impacted by foam debris. Twelve material input parameters were identified as random variables and assigned distributions. The results were generated based on 500 Monte Carlo simulations. Sensitivities and gradients for three outputs were computed. Results show that:

1) The simulations after accounting for the uncertainty in the input parameters bound the test data.
2) The gradient results for the three outputs are consistent, with ρ, **E**, $\mathbf{S_T}$, and $\boldsymbol{\sigma_T}$ dominating.
3) When accounting for the input parameter uncertainty, the sensitivities computed for the three outputs are consistent with ρ, $\mathbf{S_T}$, $\boldsymbol{\varepsilon_{fail}}$, and $\boldsymbol{\sigma_T}$ dominating the results. In addition, the tensile stress limit, $\boldsymbol{\sigma_T}$, has the largest magnitude for each output.

This work is part of an on-going evaluation utilizing probabilistic analysis to better assess structural impact simulation accuracy. The results indicate that this method shows promise for future applications. The information can be updated as new data and material models become available. Although the material modeling uncertainty was highlighted in this paper, the effect of other uncertainties, both analytical and experimental, can be determined using a similar methodology.

References

1. Gehman, H. W., *et al*: Columbia Accident Investigation Board Final Report Volume I. U. S. Government Printing Office, Washington DC, 20402-0001, August 2003.
2. Melis, M; Carney, K; Gabrys, J.; Fasanella, E.; and Lyle, K.: A Summary of the Space Shuttle Columbia Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts. Proceedings of 8th International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
3. Fasanella, E.; Lyle, K.; Gabrys, J.; Melis, M.; and Carney, K.: Test and Analysis Correlation of Foam Impact onto Space Shuttle Wing Leading Edge RCC Panel 8. Proceedings of 8th International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
4. Gabrys, J.; Schatz, J.; Carney, K.; Melis, M.; Fasanella, E.; and Lyle, K.: The Use of LS-DYNA in the Columbia Accident Investigation. Proceedings of 8th International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
5. Gordon, M. P: Leading Edge Structural Subsystem and Reinforced Carbon-Carbon Reference Manual. Boeing Document KL0-98-008, October 1998.
6. Smith, T. W. *et al*: Leading Edge Structural Subsystem Mechanical Design Allowables for Material with Improved Coating System. Loral Vought Systems Document No. 221RP00614, October 2004
7. Thacker, B. H., *et al*: Errors and Uncertainties in Probabilistic Engineering Analysis, Proceedings of the 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Non-Deterministic Approaches Forum, AIAA Paper 2001-1239, Seattle WA, April 16-19, 2002.
8. Long, M. W.; Narciso, J. D.: Probabilistic Design Methodology for Composite Aircraft Structures. DOT/FAA Report No. AR-99/2, June 1999.

9. Lyle, K. H.; Padula, S. L.; and Stockwell, A. E.: Application of Probabilistic Analysis to Aircraft Impact Dynamics. Proceedings of the 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Non-Deterministic Approaches Forum, AIAA Paper 2003-1758, Norfolk VA, April 7-10, 2003.

10. Lyle, K. H; Stockwell, A. E; and Hardy, R. C.: Application of Probability Methods to Assess Crash Modeling Uncertainty. Proceedings of the American Helicopter Society Forum, Phoenix AZ, May 6-8, 2003.

11. Periera, J.; and Revilock, D: The NASA Glenn Research Center Ballistic Impact Laboratory, Proceedings of th 54th Meeting of the Aeroballistic Range Association, Sante Fe NM, October 2003.

12. LS-DYNA Keyword User's Manual (Version 970), Livermore Software Technology Corporation, Livermore CA 94551, April 2003.

13. Carney, K.; Melis, M.; Fasanella, E.; Lyle, K.; Gabrys, J.: Material Modeling of Space Shuttle Leading Edge and External Tank Materials for Use in the Columbia Accident Investigation. Proceedings of 8th International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.

14. Using Matlab (Version 6), The Mathwork, Inc., Natick MA 01760, November 2000.