

Probabilistic Modeling of Space Shuttle Debris Impact

Luc J. Huysse^{*}, Christopher J. Waldhart[†], David S. Riha[‡], Ben H. Thacker[§],
Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78238-5166

Curtis E. Larsen^{**}
NASA Engineering and Safety Center, NASA Johnson Space Center, Houston, Texas 77058

Reynaldo J. Gomez^{††} and Phillip C. Stuart^{‡‡}
NASA Johnson Space Center, Houston, Texas 77058

On Feb 1, 2003, the Shuttle Columbia was lost during its return to Earth. As a result of the conclusion that debris impact caused the damage to the left wing of the Columbia Space Shuttle Launch Vehicle (SSLV) during ascent, the Columbia Accident Investigation Board (CAIB) recommended that an assessment be performed of the complete debris environment experienced by SSLV during ascent. Eliminating the possibility of debris is not possible; therefore, a flight rationale based on probabilistic assessment is required for the SSLV return-to-flight (RTF). A probabilistic analysis tool, based on the SwRI-developed NESSUS[®] probabilistic analysis software, predicts the probability of impact and damage to the space shuttle wing leading edge and thermal protection system components. Among other parameters, the likelihood of unacceptable damage depends on the time of release (Mach number of the orbiter) and the divot mass as well as the impact velocity and impact angle. A typical result is visualized in the figures below. Probability of impact and damage, as well as the sensitivities thereof with respect to the distribution assumptions, can be computed and visualized at each point on the orbiter or summarized per wing panel or tile zone.

I. Introduction

On Feb 1, 2003, the Shuttle Columbia was lost during its return to Earth. As a result of the conclusion that debris impact caused the damage to the left wing of the Columbia Space Shuttle Launch Vehicle (SSLV) during ascent, the Columbia Accident Investigation Board (CAIB) recommended that an assessment be performed of the complete debris environment experienced by SSLV during ascent [1]. Eliminating the possibility of debris is not possible; therefore, a flight rationale based on probabilistic assessment is required for the SSLV return-to-flight (RTF).

The primary debris sources during ascent of the Space Shuttle are the insulating foam covering the external tank (ET) and the ice that can form on the ET before and during launch. Upon detachment, aerodynamic drag forces act to slow the speed of the debris, thereby increasing the relative velocity between the debris and the orbiter. Also during transport, lift forces act to disperse the debris about their idealized trajectories. Therefore, the farther downstream the debris travels before impact, the greater the potential impact kinetic energy and crossrange (dispersion).

There are multitudes of uncertainties in the modeling of debris transport. Experimental evidence indicates that a range of debris shapes, typically thin and roughly conical, can be shed from the ET acreeage foam. In the debris transport analysis, drag models are used to predict the stochastic trajectory of the debris (zero-lift line) and impact

^{*} Principal Engineer, Materials Engineering, 6200 Culebra Road, San Antonio, Texas, Member.

[†] Research Engineer, Materials Engineering, 6200 Culebra Road, San Antonio, Texas, Member.

[‡] Principal Engineer, Materials Engineering, 6200 Culebra Road, San Antonio, Texas, Member.

[§] Director, Materials Engineering, 6200 Culebra Road, San Antonio, Texas, Associate Fellow.

^{**} NESC Discipline Expert, 1601 NASA Parkway, Houston, Texas

^{††} Technical Manager, 1601 NASA Parkway, Houston, Texas, Senior Member.

^{‡‡} Aerospace Engineer, 1601 NASA Parkway, Houston, Texas.

velocity. The crossrange scatter, characterized from experimental data, determines where the debris could potentially impact the SSLV. In addition to the debris transport uncertainties, trajectory calculations have also been shown to be highly nonlinear and highly sensitive to initial conditions.

An accurate simulation-based analysis methodology is needed that can predict with high confidence the probability of impact and damage to SSLV thermal protection system (TPS) components due to debris impact. This need can be met by developing a probabilistic methodology that takes full account of the stochastic nature of the debris size, shape and pop-off velocity; drag and crossrange models and model parameters; and impact damage to TPS components. The analysis objective was to convert existing NASA analysis models and computer codes into an end-to-end probabilistic analysis tool for the assessment of external tank debris release, impact and damage to the orbiter [2, 3]. Although the focus was mostly on the development of an analysis approach, a reliability assessment tool was built using the existing NESSUS code [4]. NESSUS allows the user to perform probabilistic analysis with both analytical models and external computer programs such as NASA’s debris transport codes.

II. Conceptual Model

The debris release, transport, and damage to the Space Shuttle TPS due to impact during ascent can be divided into a series of conditional events:

- E_1 : debris is released
- E_2 : debris impacts the TPS
- E_3 : debris impact causes damage

Failure occurs when these three events occur concurrently. Mathematically this can be expressed as the intersection of the three events:

$$\begin{aligned} \Pr(\text{failure}) &= \Pr(E_1 \cap E_2 \cap E_3) \\ &= \Pr(E_1) \Pr(E_2 | E_1) \Pr(E_3 | E_1 \cap E_2) \end{aligned} \tag{1}$$

In Equation 1, “ \cap ” denotes the intersection of events, $\Pr(E_1)$ is the probability that debris is released, $\Pr(E_2 | E_1)$ is the probability of impact given a release has occurred, and $\Pr(E_3 | E_1 \cap E_2)$ is the probability of failure (damage) given that release and impact have both occurred. These three probabilities will be referred to herein as the basic “elements” of the failure event.

Each element in Equation 1 corresponds to different modeling disciplines, i.e., debris release, debris transport and impact, and TPS damage. Numerical models that are used to predict release, transport and damage will typically account for the conditional nature of the event. For example, a computational fluid dynamics (CFD) based transport model implicitly considers the conditional event $E_2|E_1$. However, the numerical models comprising the three elements in Equation 1 will generally be correlated due to common random variables; therefore, a systems model will generally be required to assess the total probability of failure.

A. Debris Release (Event E_1)

Time-dependent probability density functions were fitted to the ET debris tables generated by the Shuttle Program at the NASA Michoud Assembly Facility. A different release table must be created for each location of interest.

B. Debris Transport and Impact (Event $E_2|E_1$)

During transport, lift forces act to disperse the debris about their idealized, or zero-lift, trajectories. Therefore, the farther downstream the debris travels before impact, the greater the crossrange or dispersion. A rotationally symmetric cross-range distribution was modeled using 6DOF CFD results generated by NASA Ames and ELORET at Mach 2.5. Depending on the foam shape and initial rotation rate either a Weibull, lognormal or truncated normal distribution provides the best fit to the CFD results. This cross-range distribution is overlaid on top of the orbiter geometry to determine the probability of impact (Figure 1).

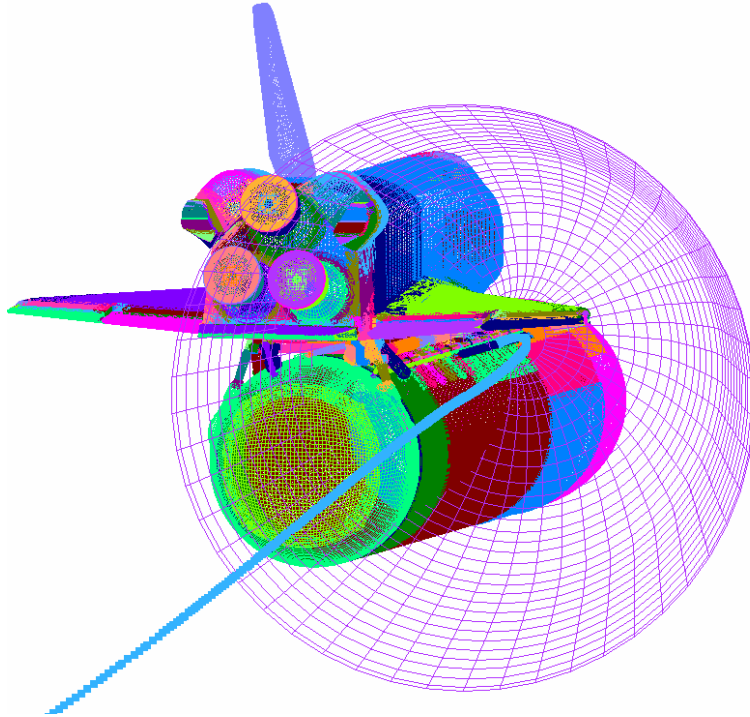


Figure 1: Zero-life life and 3-sigma cone for PAL ramp release location

C. TPS Damage (Event $E_3|E_2 \cap E_1$)

A probabilistic capability model for both the reinforced carbon-carbon (RCC) wing leading edge and the orbiter tile has been implemented. A different distribution is used depending on the nature of the impact: two types of foam and ice are considered. A normal distribution is used for RCC and a Gumbel-min distribution is used for tile. The local incidence angle is an important driver for the RCC panel capability: the capability increases as the incidence angle becomes shallower.

III. Uncertainty Modeling

A. Overview

The debris transport analysis (DTA) model is based on the NESSUS probabilistic analysis software [4]. NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) is a general-purpose tool for computing the probabilistic response or reliability of engineered systems. NESSUS can be used to simulate uncertainties in loads, geometry, material behavior, and other user-defined random variables to predict the probabilistic response, reliability and probabilistic sensitivity measures of engineered systems. The software was originally developed by a team led by SwRI as part of the NASA project entitled *Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion Components* [5].

NESSUS allows the user to perform probabilistic analysis with analytical models, external computer programs such as commercial finite element codes, and general combinations of the two. The NESSUS graphical user interface (GUI) is highly configurable and allows tailoring to specific applications. This GUI provides a capability for commercial or in-house developed codes to be easily integrated into the NESSUS framework. Eleven probabilistic algorithms are available in NESSUS including Monte Carlo simulation, first order reliability method, advanced mean value method and adaptive importance sampling [3].

NESSUS provides most well-known probability distributions as well as correlations between the random variables. These probabilistic modeling capabilities allow refinement of the analyses as probabilistic distribution

information becomes available. In addition, from the NESSUS problem statement window, it is possible to specify an area of interest (i.e. RCC panel number) and a desired Mach number. Additional random variables can easily be added. This model provides a framework for rapid parameter changes and what-if analyses.

The deterministic and probabilistic models were embedded in the NESSUS software and predict the probability of impact and damage to the space shuttle wing leading edge and thermal protection system components. A right-mouse click inside the problem definition window activates the Debris Transport Analysis (DTA) equation database (**Error! Reference source not found.**). By simply clicking on the debris release location and time of interest, the appropriate model and variable definition is created.

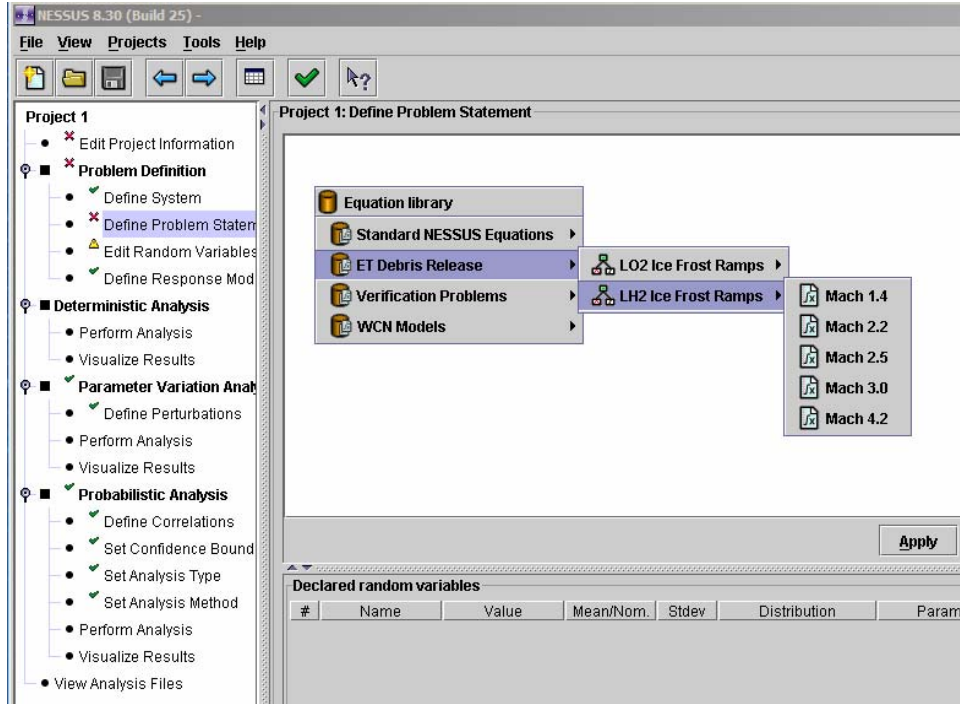


Figure 2. NESSUS problem statement window showing the NESSUS-JSC DTA model.

B. Verification with NASA-JSC DTA Model

The NESSUS-JSC DTA model was initially developed, verified and reported in Ref [2]. Typical probabilistic results are indicated on “butterfly plots” as shown in Figures 3-4. These results are shown as the lower bound of the “SwRI” results. In both figures, results from the NESSUS-DTA model (labeled “SwRI”) were in excellent agreement with the original NASA calculations (labeled NASA-JSC).

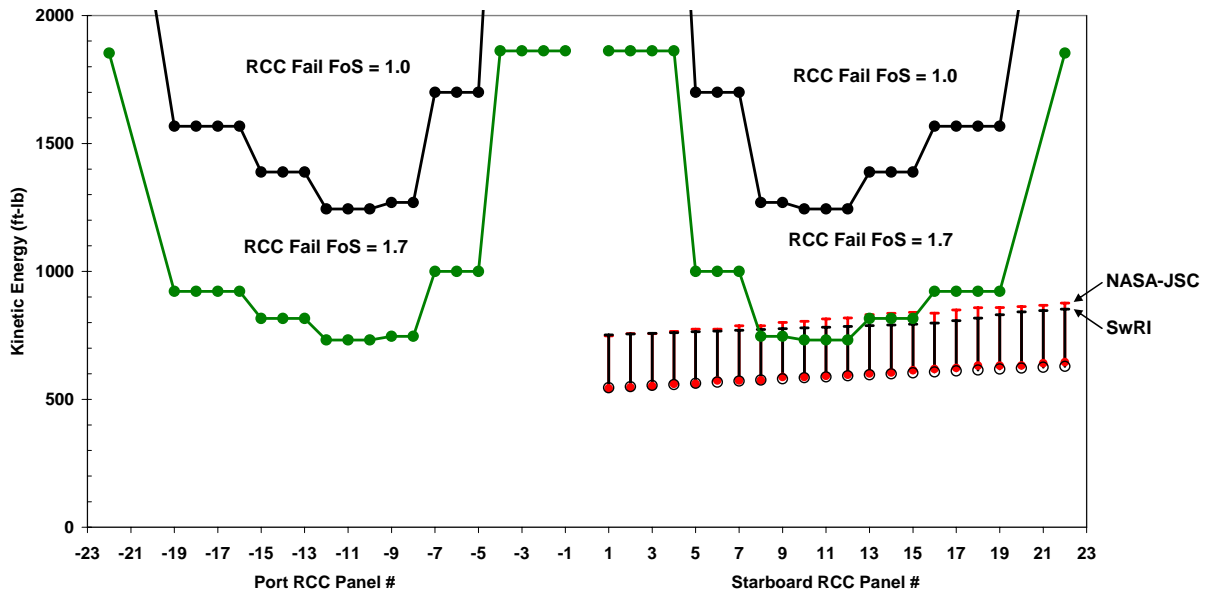


Figure 3. LO₂ PAL ramp butterfly plot.

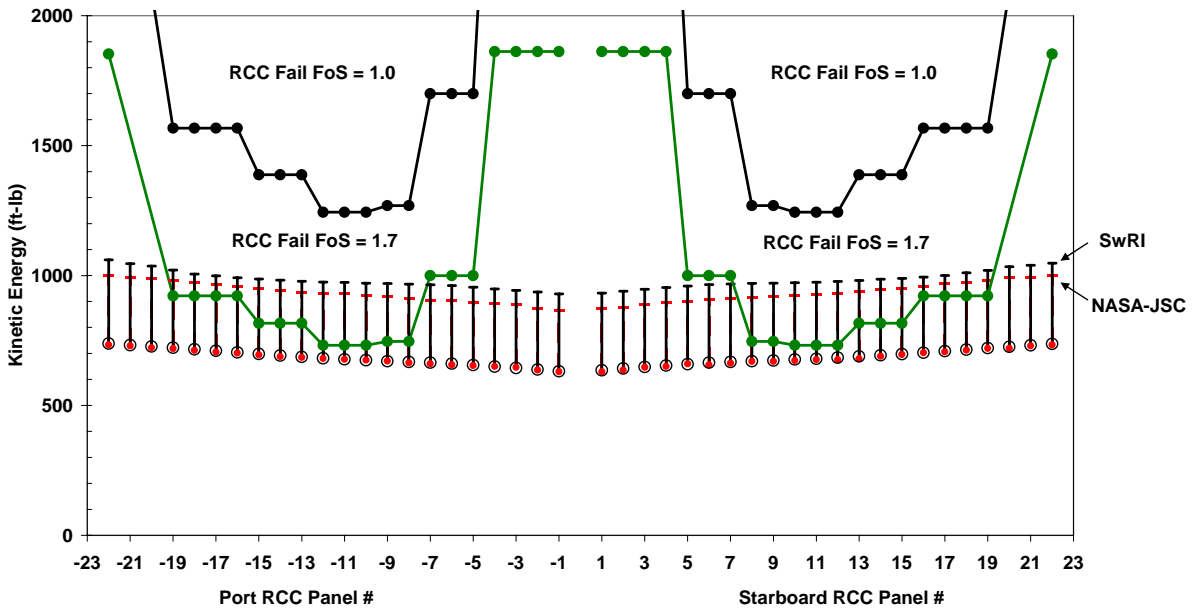


Figure 4. LO₂ intertank flange butterfly plot.

C. Probabilistic Sensitivity Analysis

In addition to the probability $\Pr(E_2 \cap E_3 | E_1)$, the code also generates plots of the sensitivity to a variety of distribution parameters such as the cross-range distribution. This is particularly of interest since the cross-range

distribution type is dependent on an unknown initial rotation rate of the debris. These sensitivities point to the key drivers in the problem and were used to guide the allocation of further modeling and analysis efforts.

Among other parameters, the likelihood of unacceptable damage depends on the time of release (Mach number of the orbiter) and the divot mass as well as the impact velocity and impact angle. A typical result is visualized in Figure 3. Probability of impact and damage, as well as the sensitivities thereof with respect to the distribution assumptions, can be computed and visualized at each point on the orbiter or summarized per wing panel or tile zone.

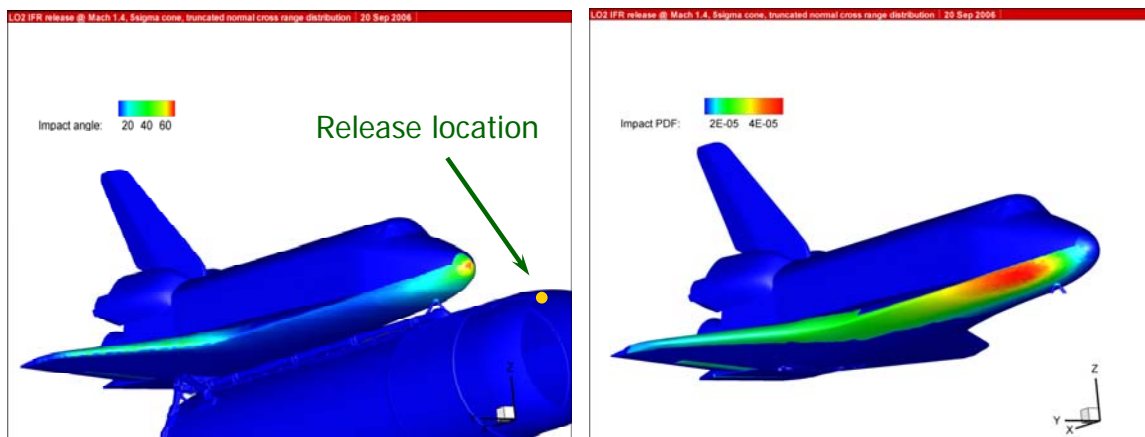


Figure 3: Typical result showing a possible release location and the impact angle (left) and probability of impact (right) to both the RCC panels and thermal protection shield on the Space Shuttle Orbiter.

The analysis tool is configured to enable quick analysis of any potential debris release event that may be recorded during the Orbiter’s ascent into space. The conditional probabilistic analysis of a debris release can be performed very quickly. For such an event the release conditions are – at least approximately – known and the probability $\Pr(E_2 \cap E_3 | E_1)$ is readily assessed.

IV. Summary and Conclusions

The probabilistic debris transport and damage analysis illustrates a practical approach to modeling conditional events. The probability of damage to the Shuttle is mitigated by including the conditions that the debris is released and that impact occurs. Accounting for all events in the sequence provides an accurate risk of failure. The probabilistic debris transport analysis specifically decoupled the release, transport, and damage events to evaluate either the probability of damage over the entire mission and orbiter, or to evaluate a specific event with a known release location, debris size, and Mach number.

V. References

- ¹Report of the Columbia Accident Investigation Board, Government Printing Office, Washington, DC. August, available online at: <http://caib.nasa.gov/>, 2003.
- ²Thacker, B.H., D.S. Riha, J.B. Fleming, L.J. Huyse, R.J. Gomez, P.C. Stuart, “Development and Verification of a Probabilistic Model for Space Shuttle Debris Transport,” Proc. 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA-2006-1778, Newport, Rhode Island, May 1-4, 2006.
- ³Huyse, L.J., Waldhart, C.J., Riha, D.S., Shuttle Debris Probabilistic Analysis: Final Report and Recommendation to the NASA Engineering Safety Center, Southwest Research Institute, San Antonio, TX, October 2006.
- ⁴NESSUS User’s Guide, v.8.4, Southwest Research Institute, San Antonio, TX, 2006
- ⁵Southwest Research Institute, “Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion System Components,” Final Report, NASA Contract NAS3-24389, NASA Lewis Research Center, Cleveland, Ohio, 1995.