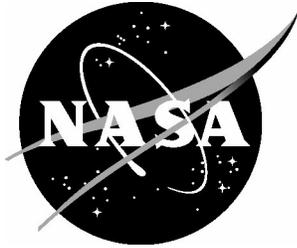


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ARL-TR-3348



The Influence of Projectile Trajectory Angle on the Simulated Impact Response of a Shuttle Leading Edge Wing Panel

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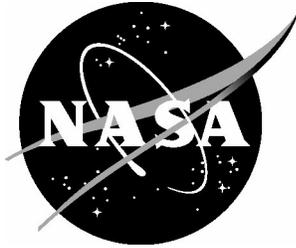
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Abstract

In support of recommendations by the Columbia Accident Investigation Board, a team has been conducting an extensive analysis effort to study the effect of debris impacting the reinforced carbon-carbon panels of the shuttle leading edge. Various parameter studies have been conducted to define the scope of this analysis. The objective of the study described within this document was to examine the effect of varying parameters of the debris trajectory on the damage tolerance. Three locations were examined including the upper and lower surface and the apex of the leading edge. For each location, trajectory variances were identified for both the alpha and beta directions. A 2"x7"x11.88" rectangular foam block weighing 0.23 lb was used to impact the RCC. The material model of the foam was developed at GRC using LS-Dyna Mat 83 (MAT_FU_CHANG_FOAM, GFM4). The impact velocity for the foam was 1000 ft/sec. The results of the analysis indicated in all cases the beta sweep decreased the amount of damage to the panel. This is due to the fact the trajectory parameter could only vary in a way to cause a more glancing blow in the beta direction. For the alpha variations, the trajectory parameter was varied in a way to result in a more severe impact. In these cases, there was significant increase in damage to the RCC panel. In particular, for the lower surface, where the alpha can increase by 10 degrees, there was a nearly 40% increase in the impulse. As a result, it is recommended that for future analyses, a 10 degree offset in alpha from the nominal trajectory is included for impacts on the lower surface. It is also recommended to assume a straight aft, or zero beta, trajectory for a more conservative analysis.

Introduction

The Columbia Accident Investigation Board (CAIB) concluded that the breach of the shuttle TPS was caused by a large piece of External Tank (ET) foam that impacted and penetrated the lower portion of a left-wing leading edge RCC panel, as shown in Figure 1. Chapter 11 recommendation 3.3-2 of the CAIB report [1] indicates that NASA should initiate a program to improve the impact resistance of the Wing Leading Edge (WLE) and to “determine the actual impact resistance of current materials and the effect of likely debris strikes.” To address this recommendation and to prepare for return to flight, a detailed study of the foam impact on the leading edge surfaces was initiated to characterize potential damage and limitations for future flights. A team consisting of NASA Glenn Research Center, NASA Langley Research Center, and Boeing Philadelphia was formed to study the effect of high speed foam impacts on the Reinforced Carbon-Carbon (RCC) WLE panels. The objective of the team was to develop analytical tools that could be used to accurately predict the threshold of damage from debris for the WLE panels for a variety of impact conditions. This threshold of damage is defined in terms of impact velocity for a standardized debris size and mass.

Pursuant to the recommendations of the CAIB report, the team has been developing LS-DYNA [2] models of the RCC leading edge panels and correlating the models with data obtained from impact tests onto RCC

panels. The analysis discussed within this document is a part of a larger parametric study intended to define analytical requirements for the large scale simulation effort. In an attempt to bound the large number of possible cases to be studied, the parameter study helped define a reasonable number of conditions that would limit the problem to a workable number of loading conditions. An analysis of a rectangular foam block impacting panel 9 was used as the baseline in the study. This particular parameter study was intended to address the assumption that the foam would be traveling along a trajectory parallel to the x-axis, or straight aft. The possibility of a slight rotation in the pitch or sweep angle needed to be addressed. This report summarizes the finding of this parametric study.

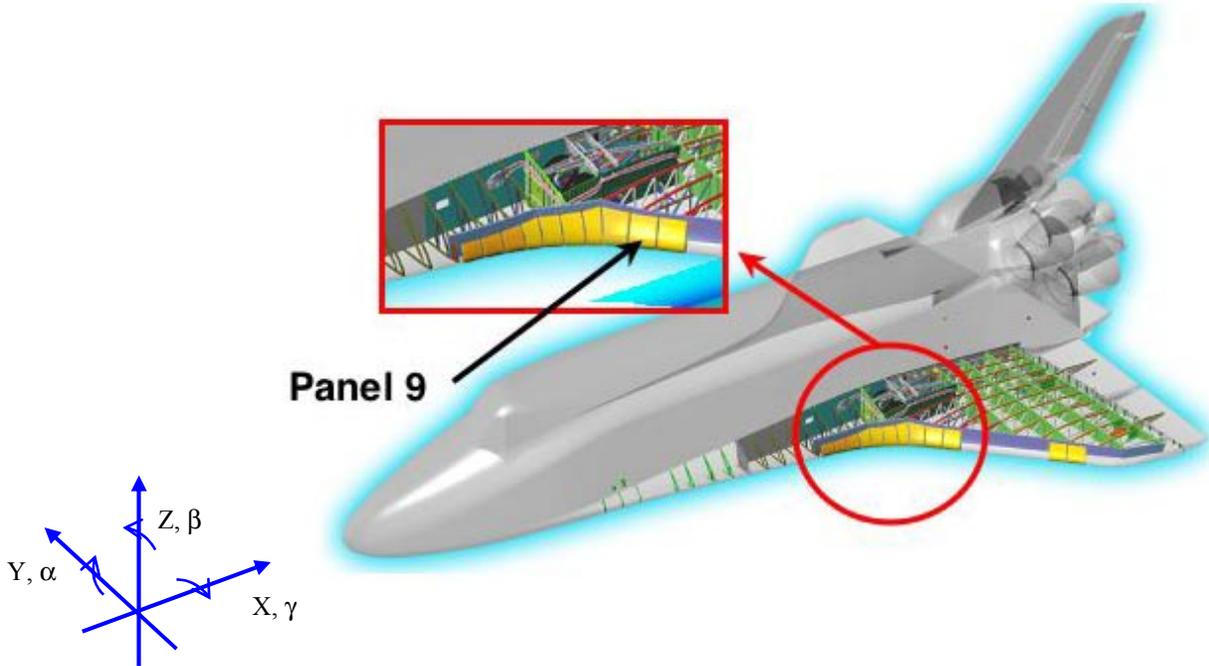


Figure 1: Wing Leading Edge

Analytical Approach

This study was intended to address possible variations in the trajectory of the projectile. Previous analyses had assumed the projectile would impact the velocity in a direction parallel to the axis of the vehicle body, or the velocity vector of the orbiter itself. For this analysis, variances in this trajectory were considered for two possible rotations from this vector. The coordinate system of the orbiter along with the rotation angles is shown in Figure 1. Rotation about the y-axis, defined as α , or commonly referred to as the pitch angle, was the first variable. The second variable was possible rotation about the z-axis, defined as β , or commonly referred to as sweep angle or yaw. Rotation about the x-axis, γ , or bank, was addressed in a separate parameter study. The effects of the change in the α and β angles were addressed at three locations on panel 9. These locations were on the top surface (location 104), bottom surface (location 4) and the apex (location 2). These locations are shown in Figure 2 for a cross section of the panel. All three locations lie along the midspan of the panel.

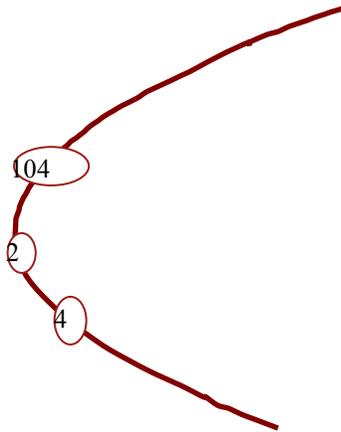


Figure 2: Impact Locations for Trajectory Study

Analysis of trajectory parameters and transport uncertainties of the debris by the Orbiter project defined a given set of α and β rotation angles to be used in this parameter study. This report indicated a maximum variance in the β angle of 5 degrees sweep outboard. Because the model was of panel 9 from the left wing, a negative angle is used. This would be the same for both lower and upper surfaces. The report also indicated a maximum possible variance in the pitch angle, α , of 5 degrees for the upper surface and 10 degrees for the lower surface. The combination of rotations to be addressed is listed in Table 1. Note, for this analysis, the effect of an α or β rotation are considered separately. No cases involving a rotation about both axes combined were considered.

Table 1: Parameter Study Variables

| Location | α | β |
|-----------------|----------|---------|
| 2 | 0 | 0 |
| (apex) | 0 | -5 |
| 4 | 0 | 0 |
| (lower surface) | -5 | 0 |
| | -10 | 0 |
| | 0 | -5 |
| 104 | 0 | 0 |
| (upper surface) | 5 | 0 |
| | 0 | -5 |

To impose the change in trajectory for the projectile, the foam was rotated the corresponding angle about the given axis. These rotations could be defined either about the orbiter axis or a local axis. By rotating about the orbiter coordinate system origin, the projectile would be relocated on a global scale and would require large translations to reposition it to impact at the correct location. However, by using the local axis, the need for this translation was eliminated. The resulting foam orientation was only minimally different between the two approaches. To generate the local rotation, a coordinate system was generated at the desired point of impact with the same orientation of the orbiter coordinate system. The foam projectile was then rotated about the corresponding axis of this local coordinate system. For all cases, it was assumed that the beta translation resulted in a more glancing blow, aligning with the sweep of the wing. The alpha translation was assumed to result in a more direct impact. For this reason, the direction of rotation for the upper and lower surfaces are

opposite in direction.

An LS_DYNA model was used to analyze the effect of a foam projectile impacting a wing leading edge panel on the upper surface, lower surface, and apex. The effect of the different trajectory variations was observed for each of the three locations. Panel 9 is shown in Figure 3 with the foam configured for an impact at location 4. The four different orientations of the foam at this location are shown in this figure.

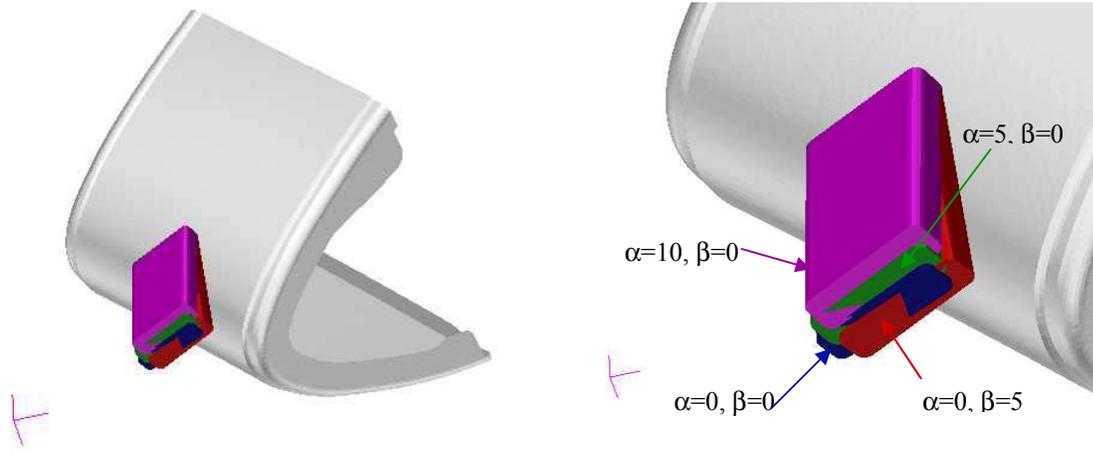


Figure 3: Panel 9 with Foam Impact at Location 4

Model Description

The LS-DYNA analysis model consists of two components, an RCC Panel 9 and a foam block. The model with the foam at location 4 is shown in Figure 4. Both the panel and foam block models utilized were products of previous studies in support of the overall Impact Team effort. The Panel 9 geometry included the midsection, ribs, and bottom flanges. The model was constrained at the bolt hole locations. The model consists of 57,414 shell elements. Average-strength, degraded material properties were used for the RCC panel. The material model was developed by team members using LS-Dyna Mat 58(MAT_LAMINATED_COMPOSITE_FABRIC [3]).

The projectile was a 2"x7"x 11.88" rectangular foam block with rounded edges. It is modeled with 21,899 solid elements. The material model of the foam was also developed by team members at NASA GRC using LS-Dyna Mat 83 (MAT_FU_CHANG_FOAM, GFM4) [3]. The weight of the foam projectile was 0.23 lb and the impact velocity was 1000 ft/sec. The velocity vector is input in global coordinates. Therefore, the values were modified to account for the varying trajectory angles. The components of the velocity used in the analyses are shown in Table 2 below.

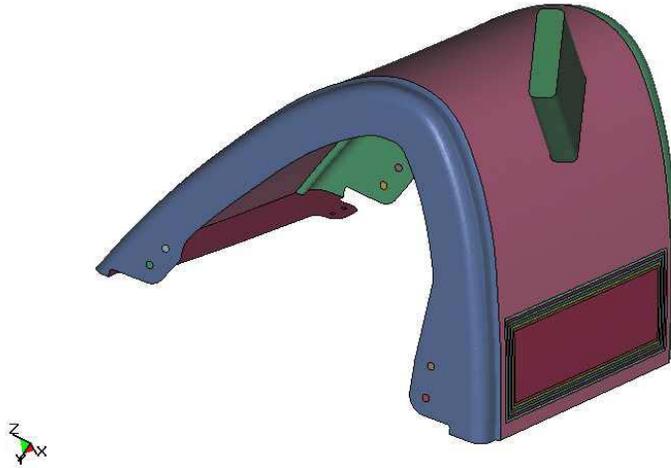


Figure 4: RCC Panel 9 LS Dyna Model with Foam at Location 4

Table 2: Velocity Components

| Location | Angle | | Vx, in/sec | Vy, in/sec | Vz, in/sec |
|----------|----------|----------|--------------|------------|------------|
| | Alpha | Beta | | | |
| 104 | 0 | -5 | 11954 | -1046 | 0 |
| | 0 | 0 | 12000 | 0 | 0 |
| | 5 | 0 | 11954 | 0 | -1046 |
| 2 | 0 | -5 | 11954 | -1046 | 0 |
| | 0 | 0 | 12000 | 0 | 0 |
| 4 | 0 | -5 | 11954 | -1046 | 0 |
| | 0 | 0 | 12000 | 0 | 0 |
| | -5 | 0 | 11954 | 0 | 1046 |
| | -10 | 0 | 11818 | 0 | 2084 |

Results

The contact force for the various load cases are plotted as time histories in Figures 5 through 7. These graphs compare the change in contact force for the different trajectory parameters at locations 104, 2, and 4, respectively. From these graphs, it is evident that the contact force decreases in all cases for the beta sweep of 5 degrees. This is an expected result in that the sweep rotation results in a higher obliquity impact, or more glancing blow, to the panel. The alpha or pitch rotations result in an increase in contact force. In particular, for location 4, the increase is significant. Table 3 compares the impulse based on this contact force. For location 4, there is a 21% increase in impulse for 5 degrees of pitch, and a 40% increase for 10 degrees of pitch. Based on this result, it is apparent the pitch rotation is especially significant for location 4. The effect of the pitch angle is less severe for location 104 at only a 7.3% increase from the baseline. The difference in effects between location 104 and location 4 is more than likely due to the difference in the curvature of the panel between the top and bottom surface. Also shown in Table 3 is the impact angle of the foam. The impact angles listed here are relative to an impact becoming more severe as it approaches a 0 degree angle, and more glancing as the angle approaches 90 degrees. For the baseline trajectory, Location 4 on the lower side of the panel has an impact angle of 67.4 degrees, whereas location 104 on the upper surface has an impact angle of

55.3 degrees. The higher the impact angle, the more oblique (tangent) the velocity vector is. This results in an obvious decrease in the impulse. However, it is of interest to note that for location 4 on the lower surface the impulse level is much more sensitive to a change in the impact angle than location 104.

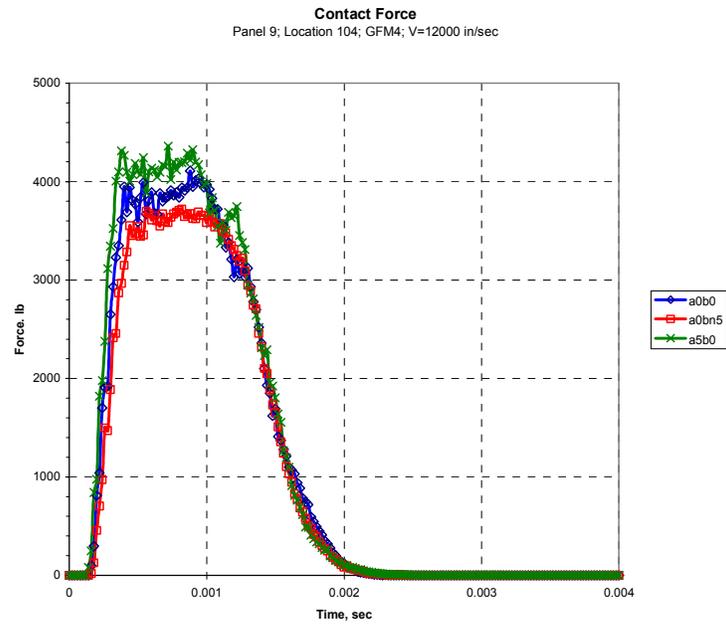


Figure 5: Contact Force Results, Location 104

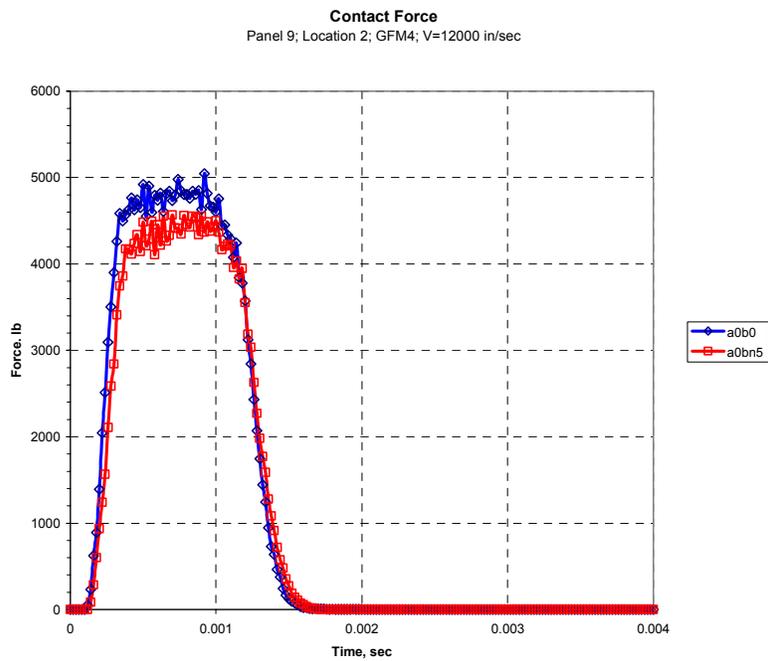


Figure 6: Contact Force Results, Location 2

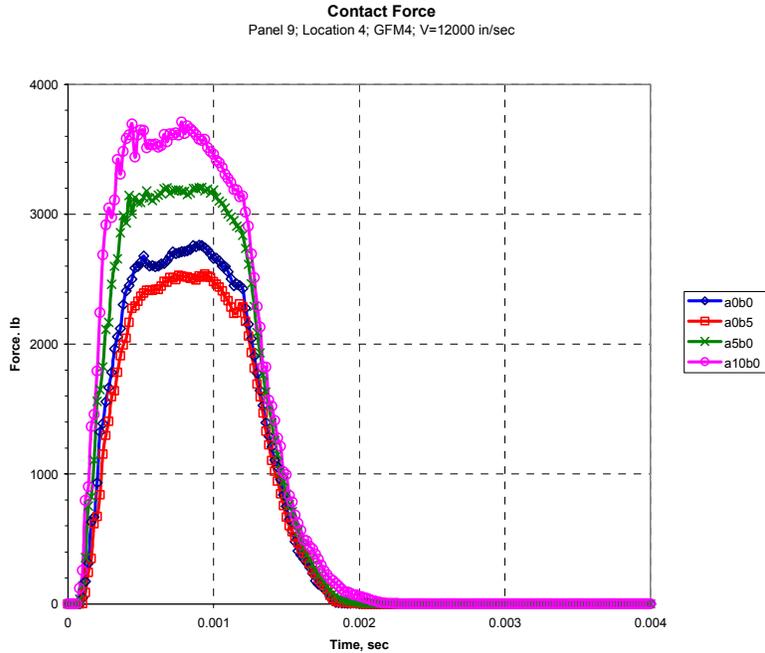


Figure 7: Contact Force Results, Location 4

Table 3: Impulse Results

| Location | Angle | | Impact Angle* | Impulse lb-sec | Impulse % Change |
|----------|----------|----------|---------------|----------------|------------------|
| | Alpha | Beta | | | |
| 104 | 0 | 5 | 58.7° | 4.35 | -7.1% |
| | 0 | 0 | 55.3° | 4.68 | -- |
| | -5 | 0 | 51.6° | 5.02 | 7.3% |
| 2 | 0 | 5 | 51.6° | 4.5 | -8.2% |
| | 0 | 0 | 46.7° | 4.9 | -- |
| 4 | 0 | 5 | 69.8° | 2.80 | -8.5% |
| | 0 | 0 | 67.4° | 3.06 | -- |
| | 5 | 0 | 63.0° | 3.71 | 21% |
| | 10 | 0 | 58.7° | 4.28 | 40% |

*A 90 degree impact represents the foam skimming tangent to the surface, where a 0 degree impact represents the foam impacting normal to the surface.

Time history graphs of kinetic energies, internal energies, and the hourglass energy are all included in the appendix. Each of these results indicates similar trends to the one discussed above for contact force. In each case, the increased beta angle reduces the effect of the impact on the RCC panel. The increase in alpha angle has the reverse effect. Additionally, the lower side consistently shows a higher sensitivity to the increased impact angle than the upper surface.

Contour plots showing the first principal infinitesimal strain at different time steps are also included in the appendix. In these plots, the spectrum is defined to have a maximum of 0.006 in/in. This represents the approximate failure strain of the RCC material. Therefore, areas of the plots that are colored red indicate imminent failure of the RCC. Elements that have reached the failure criteria are deleted. These contour plots

of first principal infinitesimal strain show more resulting damage in the RCC panel for the off nominal alpha angle. This increase in damage is especially significant for the lower surface as shown in the plots for location 4.

Conclusions

The results of the parametric study have been outlined and discussed above. Based on these results, it is apparent that the alpha rotation of the foam projectile does have a detrimental effect on the damage to the RCC panel. In particular, at location 4, this can have a much greater influence on the threshold velocity. Because of this, impact analysis of future panels at the location 4 should include a rotation in the pitch direction. The beta angle reduces the effect of the impact. Therefore, it is a more conservative solution to assume a zero beta (straight aft) trajectory.

References

1. Gehman, H. W., et al, "Columbia Accident Investigation Board," Report Volume 1, U. S. Government Printing Office, Washington, DC, August 2003.
2. Anon., "LS-DYNA Keyword User's Manual Volume I and II – Version 960," Livermore Software Technology Company, Livermore, CA, March 2001.
3. Carney, K., Melis, M., Fasanella, E., Lyle, K, and 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.

APPENDIX

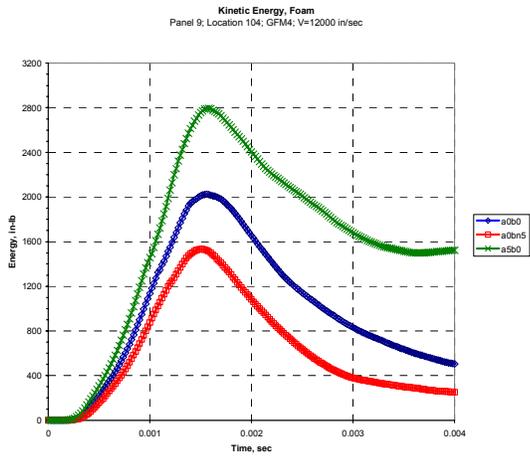


Figure A8: RCC Kinetic Energy, Location 104

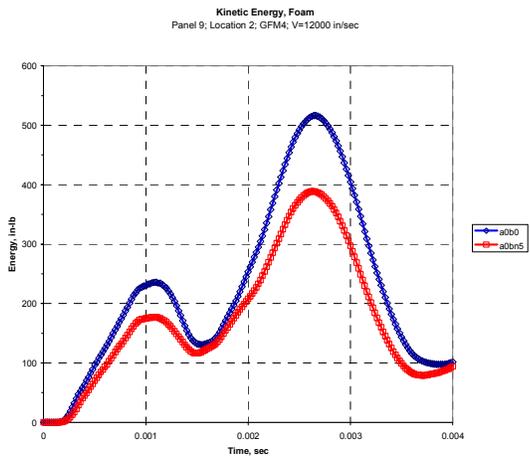


Figure A9: RCC Kinetic Energy, Location 2

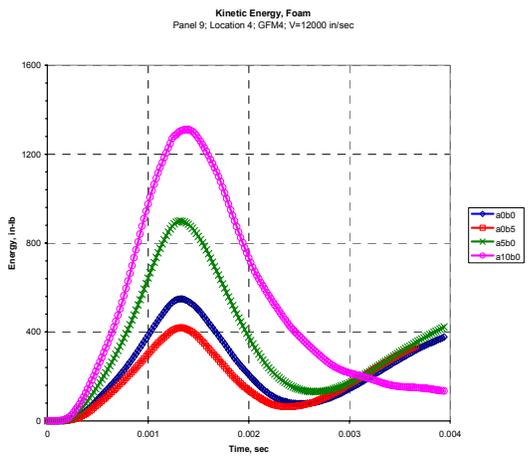


Figure A10: RCC Kinetic Energy, Location 4

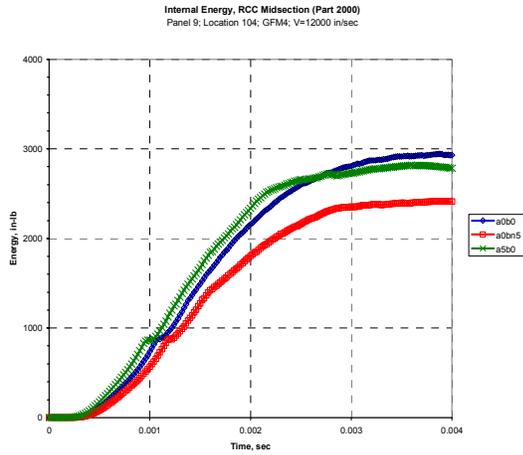


Figure A4: RCC Internal Energy, Location 104

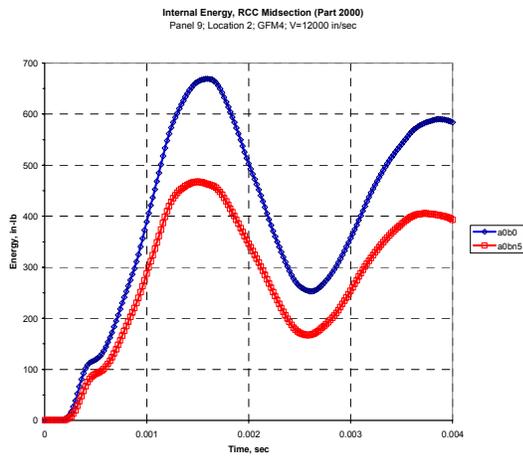


Figure A5: RCC Internal Energy, Location 2

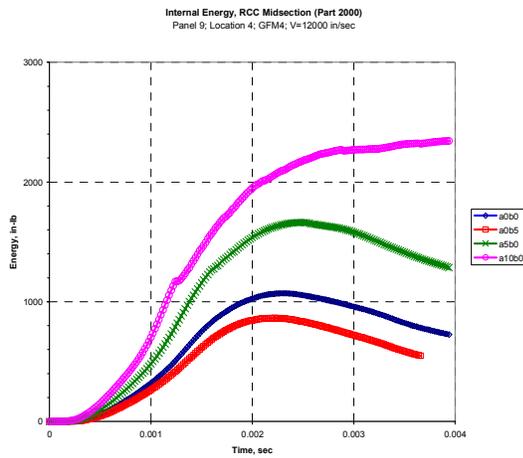


Figure A6: RCC Internal Energy, Location 4

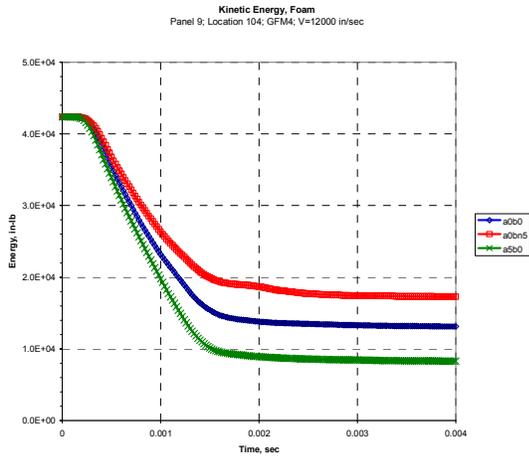


Figure A7: Foam Kinetic Energy, Location 104

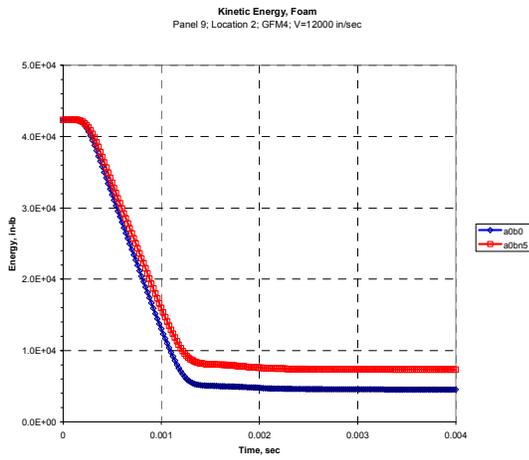


Figure A8: Foam Kinetic Energy, Location 2

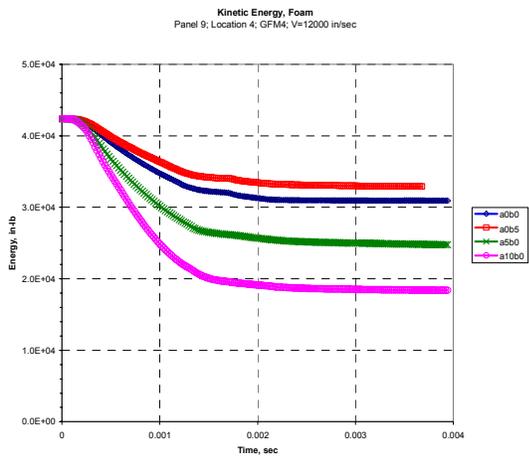


Figure A9: Foam Kinetic Energy, Location 4

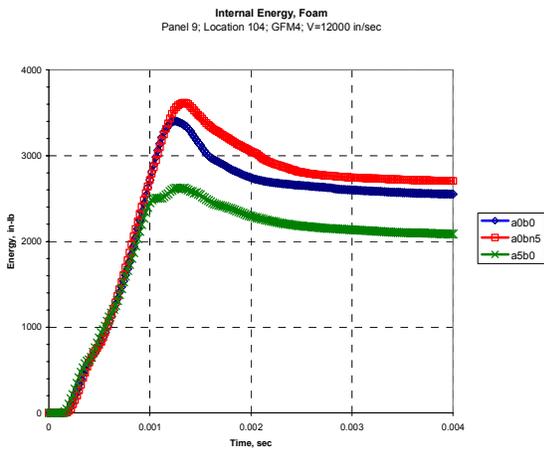


Figure A10: Foam Internal Energy, Location 104

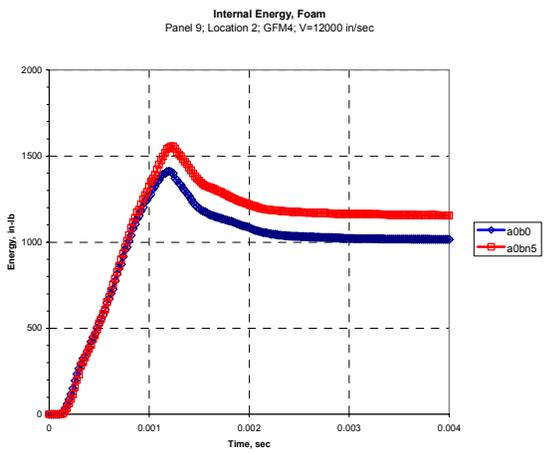


Figure A11: Foam Internal Energy, Location 2

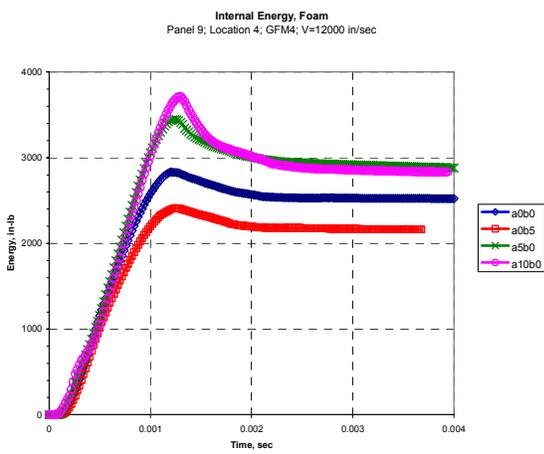


Figure A12: Foam Internal Energy, Location 4

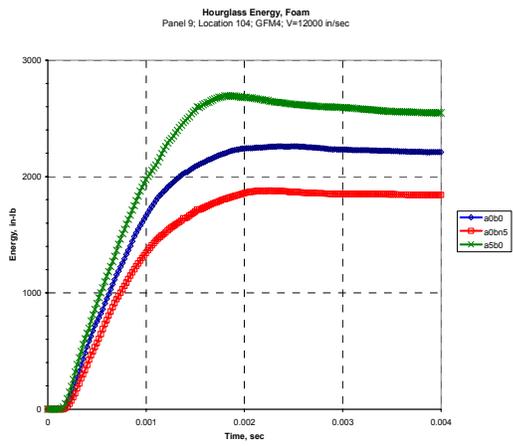


Figure A13: Hour Glass Energy, Location 104

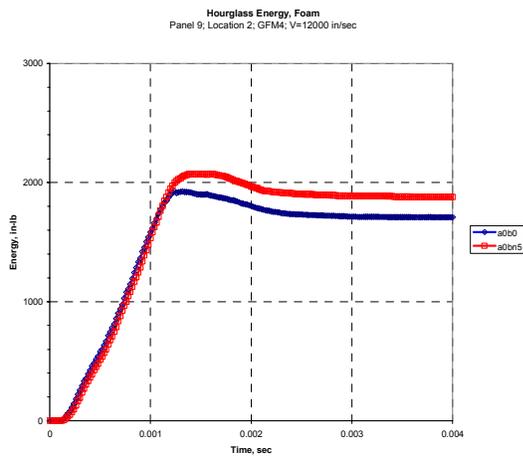


Figure A14: Hour Glass Energy, Location 2

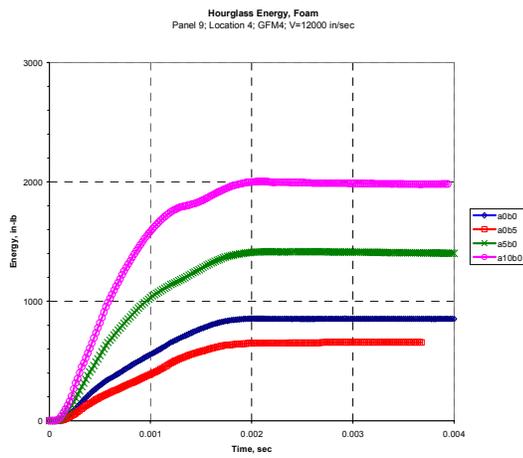


Figure A15: Hour Glass Energy, Location 4

**Comparisons of First Principal Strain
(Panel 9, Location 104)**

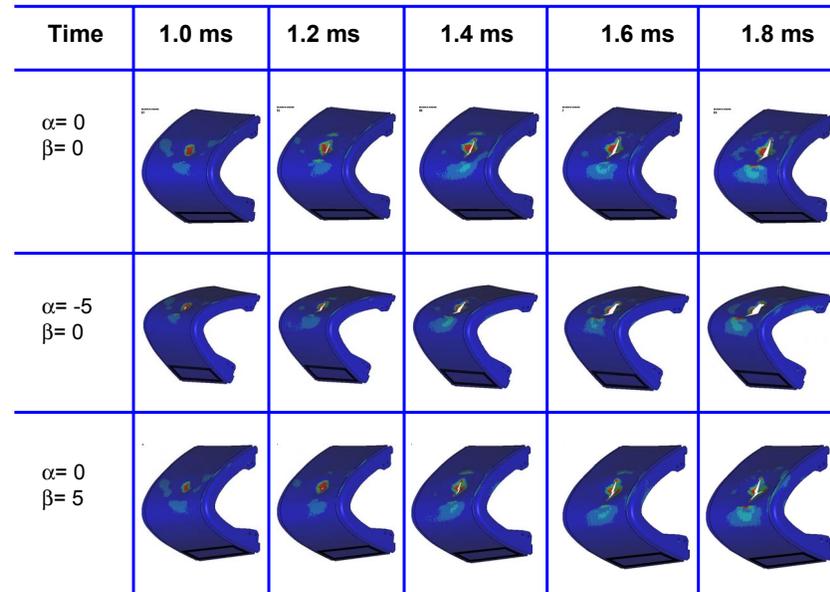


Figure A16: First Principal Strain, Location 104

First Principal Strains

Loc 2

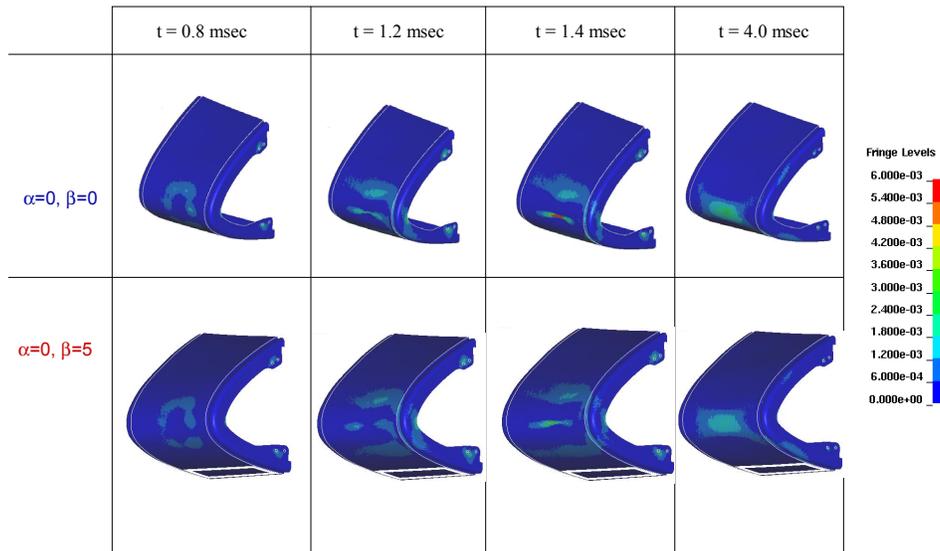


Figure A17: First Principal Strain, Location 2

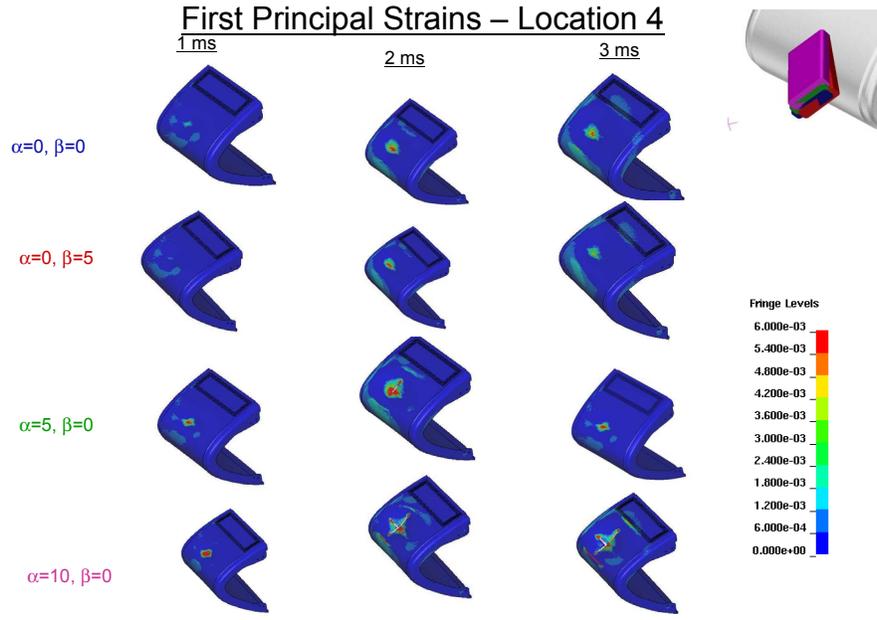


Figure A18: First Principal Strain, Location 4

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| 14. ABSTRACT In support of recommendations by the Columbia Accident Investigation Board, a team has been studying the effect of debris impacting the reinforced carbon-carbon panels of the shuttle leading edge. The objective of this study was to examine the effect of varying parameters of the debris trajectory on the damage tolerance. Impacts at the upper and lower surface and the apex of the leading edge were examined. For each location, trajectory variances included both the alpha and beta directions. The results of the analysis indicated in all cases the beta sweep decreased the amount of damage to the panel. The increases in alpha resulted in a significant increase in damage to the RCC panel. In particular, for the lower surface, where the alpha can increase by 10 degrees, there was a nearly 40% increase in the impulse. As a result, it is recommended that for future analyses, a 10 degree offset in alpha from the nominal trajectory is included for impacts on the lower surface. It is also recommended to assume a straight aft, or zero beta, trajectory for a more conservative analysis. | | | | | |
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