

# A Summary of the Space Shuttle Columbia Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts

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## Abstract

*On February 1, 2003, the Space Shuttle Columbia broke apart during reentry resulting in loss of 7 crewmembers and craft. For the next several months an extensive investigation of the accident ensued involving a nationwide team of experts from NASA, industry, and academia, spanning dozens of technical disciplines.*

*The Columbia Accident Investigation Board (CAIB), a group of experts assembled to conduct an investigation independent of NASA concluded in August, 2003 that the cause of the loss of Columbia and its crew was a breach in the left wing leading edge Reinforced Carbon-Carbon (RCC) thermal protection system initiated by the impact of thermal insulating foam that had separated from the orbiters external fuel tank 81 seconds into the missions launch. During reentry, this breach allowed superheated air to penetrate behind the leading edge and erode the aluminum structure of the left wing which ultimately led to the breakup of the orbiter.*

*In order to gain a better understanding of the foam impact on the orbiters RCC wing leading edge, a multi-center team of NASA and Boeing impact experts was formed to characterize the foam and RCC materials for impact analysis using LS-DYNA. LS-DYNA predictions were validated with sub-component and full scale tests. LS-DYNA proved to be a valuable asset in supporting both the Columbia Accident Investigation and NASA's return to flight efforts.*

*This paper summarizes the Columbia Accident and the nearly seven month long investigation that followed. The use of LS-DYNA in this effort is highlighted. Contributions to the investigation and return to flight efforts of the multi-center team consisting of members from NASA Glenn, NASA Langley, and Boeing Philadelphia are covered in detail in papers to follow in these proceedings.*

## The Accident

On January 16, 2003, at 10:39 a.m. Eastern Standard Time, the Space Shuttle Columbia lifted off from Launch Complex 39-A at Kennedy Space Center in Florida. At approximately 82 seconds into launch, Columbia was traveling at Mach 2.46 (1,650 miles per hour) at an altitude of nearly 66,000 feet when it was struck by a large piece of foam that had separated from the shuttle's external fuel tank. The foam, decelerated by the air flow past the Orbiter, struck the left wing leading edge of Columbia at a relative speed of 416 to 573 miles per hour causing the breach in the leading edge thermal protection system that ultimately led to the tragedy. Two movie cameras captured the event. Figure 1 is an image taken from one of the movies just after the event that depicts the particle cloud of foam resulting from the impact.

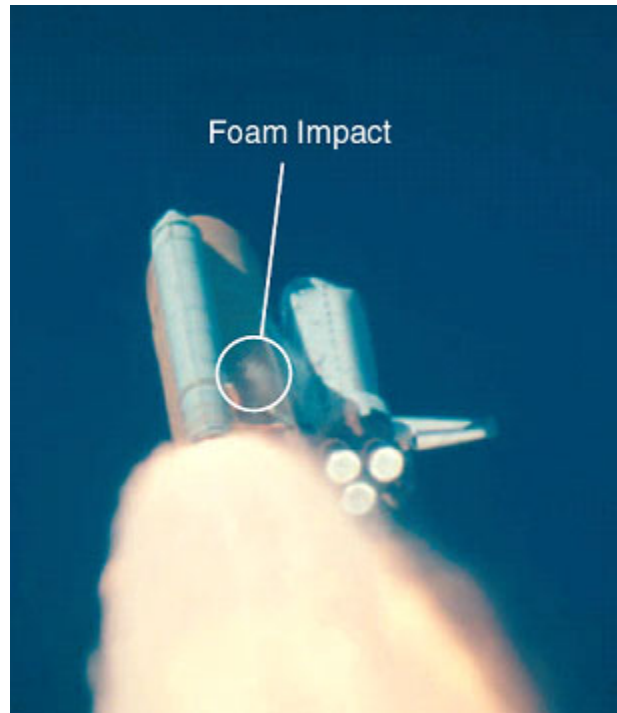


Figure 1. Debris cloud resulting from External Tank foam impact on Orbiter left wing leading edge.

## Background

The Shuttle launch system, commonly referred to as the launch stack consists of three components: The Solid Rocket Boosters (SRB's), the External Fuel Tank (ET), and the Orbiter. The ET contains the cryogenic liquid hydrogen and oxygen propellants that feed the three Space Shuttle Main Engines located at the rear of the orbiter. Various types of insulating foams cover the majority of the ET to keep the propellants cold and prevent the formation of ice on the outside of the tank. The foam accounts for the ET's characteristic deep orange color as these foams quickly turn orange when exposed to sunlight. Most areas on the ET require only an inch or so of foam, which is typically sprayed on by machine. Some locations, however, require more substantial build-ups of foam and are applied by hand. The Bipod Attachment is one such location and is considered to be the source of the foam debris. The foam at this location was made from a polyurethane formulation designated BX-250.

The Orbiter is attached to the External Tank at three locations: Two support points at the rear of the vehicle, and one at the front, which is referred to as the Bipod. The Bipod consists of two struts connecting the front of the orbiter to the ET. The Bipod attachment at the ET requires additional insulation which is applied in the shape of a ramp to account for aerodynamics. This foam build-up is referred to as the Bipod Ramp. Figure 2 highlights the Bipod, the Bipod Ramp, and the general impact location on Columbia's left wing leading edge.



Figure 2. Shuttle Columbia just after liftoff showing the Bipod Attachment, the Bipod Ramp and the location of Impact.

During reentry, the wing leading edges of the Orbiter are expected to see temperatures up to 3000 Degrees Fahrenheit and are thermally protected through the use of a brittle composite material called Reinforced Carbon-Carbon (RCC).

Each orbiter wing has 22 unique panels made by hand for its specific location on the wing. The gaps between these panels are sealed with a structure, also made of RCC, called a T-Seal. Figure 3 shows a graphic of several panels on an orbiter wing leading edge spar, and Figure 4 provides a closer view of a single leading edge panel with a T-Seal.

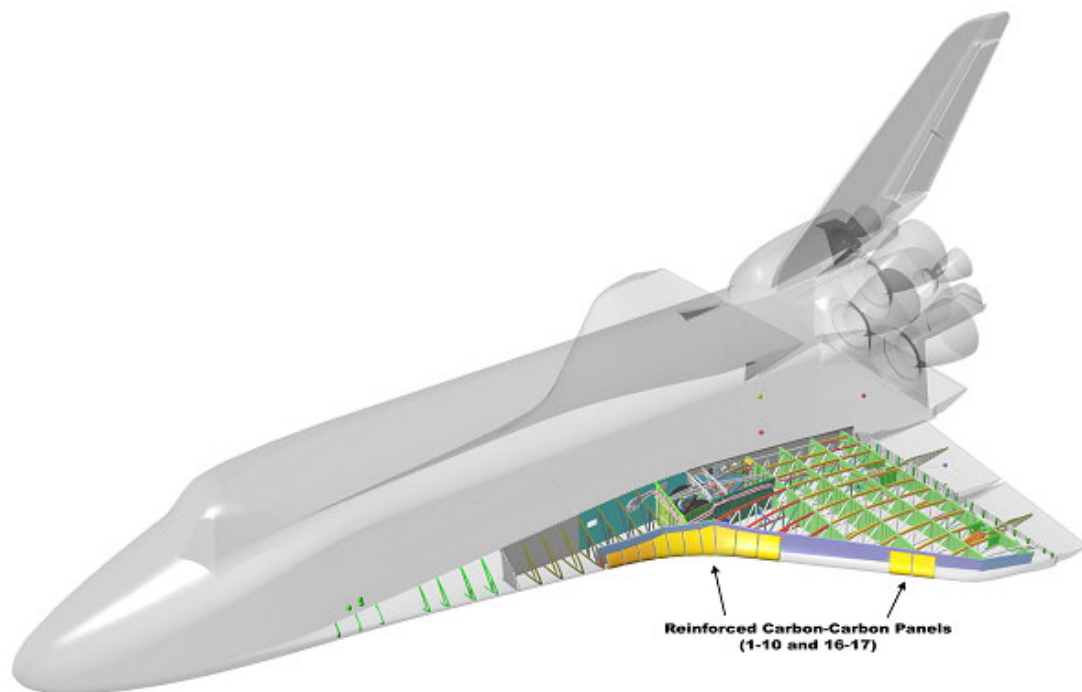


Figure 3. Reinforced Carbon-Carbon panels (in yellow) are attached on the Orbiter leading edges.

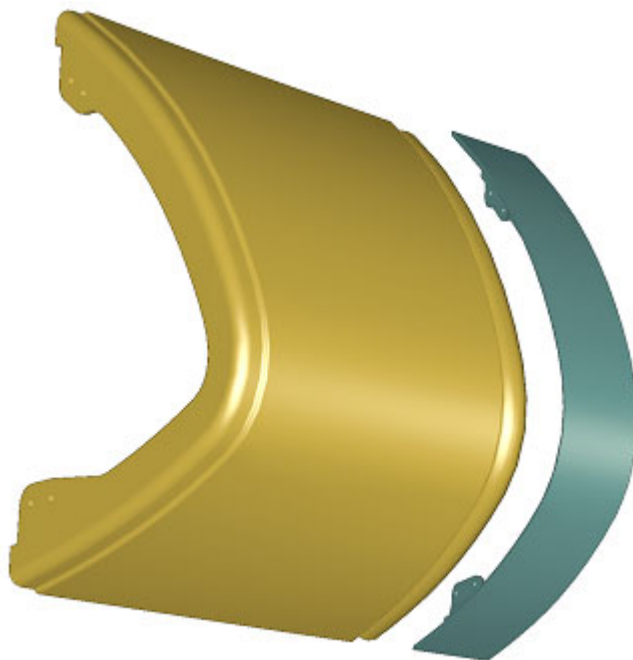


Figure 4. Reinforced Carbon-Carbon panel (in yellow) shown with T-Seal (in blue).

An exhaustive reconstruction effort of the Orbiter wreckage provided evidence that a breach in Columbia's wing leading edge, which was a likely result of the foam impact event. The investigation to follow quickly established the need to understand the impact behavior of External Tank foam and Reinforced Carbon-Carbon both from an experimental and computational standpoint. Many methodologies were considered for characterizing and predicting ET foam impacts on RCC leading edges. Ultimately, LS-DYNA was selected as the computational tool to support the accident investigation and NASA's current return to flight effort. Little was known, at that time, about the impact characteristics of either BX-250 or RCC.

### **LS-DYNA's Role in the Accident Investigation**

Once it was determined that ET foam debris from the Bipod Ramp was a likely cause of the leading edge breach, the CAIB [1] began an aggressive test program at Southwest Research Institute (SwRI) to build a full-scale test article of a segment of an Orbiter leading edge for impact testing. RCC panels from the remaining Orbiters that had similar mission histories to those on Columbia were used for the testing. Figures 5 and 6 show the test range and the full-scale test article, respectively, at SwRI.

NASA called for the development of an analysis capability, using LS-DYNA, to predict BX-250 impacts on RCC materials to support the full-scale test program and eventually the return to flight efforts. Individuals from NASA Glenn, NASA Langley, and Boeing Philadelphia all experienced with LS-DYNA impact analysis formed a team to address this computational challenge. Several technical hurdles needed to be overcome to develop such a capability: 1) The characterization of BX-250 and RCC impact behavior and the development of LS-DYNA material models for each. 2) Validating the material models against sub-scale and full-scale test results. 3) Understanding LS-DYNA sensitivity and uncertainty to various parameter inputs and meshing.

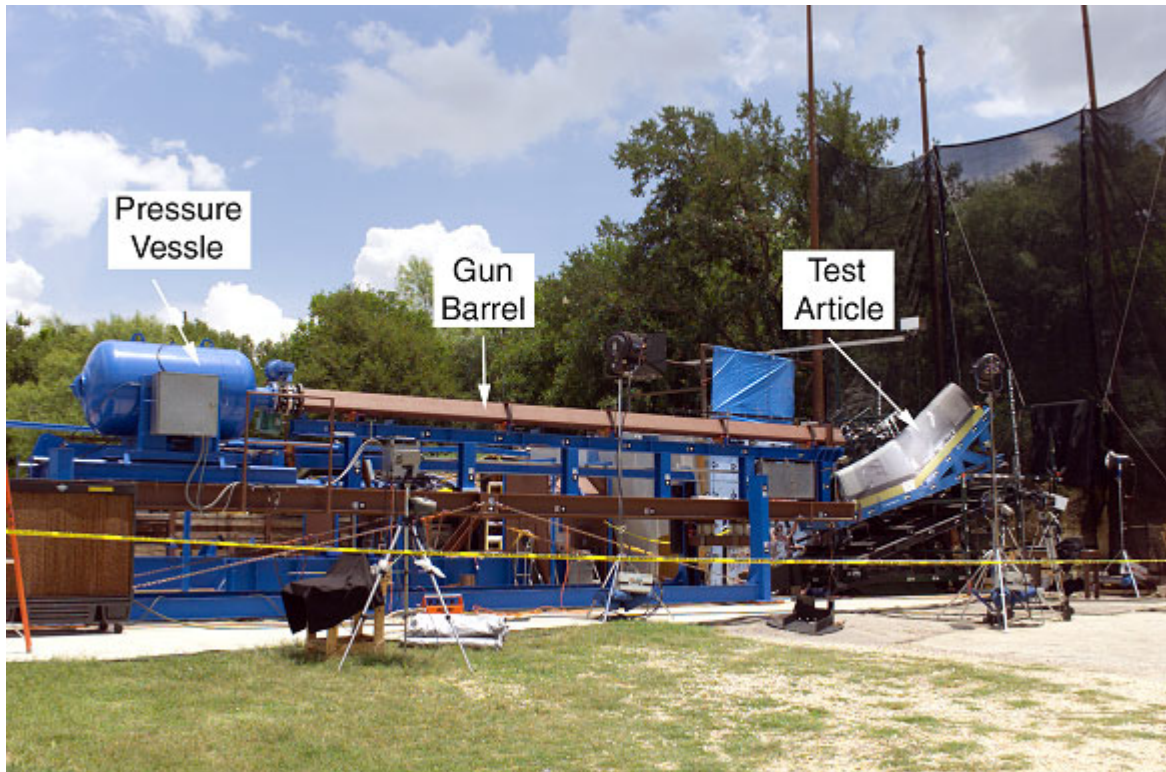


Figure 5. Ballistic test range at Southwest Research Institute showing gas gun and full-scale Orbiter leading edge test article.



Figure 6. Full-scale Orbiter leading edge test article at Southwest Research Institute ballistic range.

The material model for the BX-250 foam was developed out of static and dynamic testing as well as sub-scale impact tests on load cells [2]. Figure 7 shows the comparison of a BX-250 impact test on an aluminum plate as compared with the LS-DYNA prediction. The RCC composite material model was initially based on limited static stress-strain data. Current work is underway to determine high strain rate behavior for RCC to enhance the model. References 2 and 3, presented in these proceedings, highlight this work in detail.

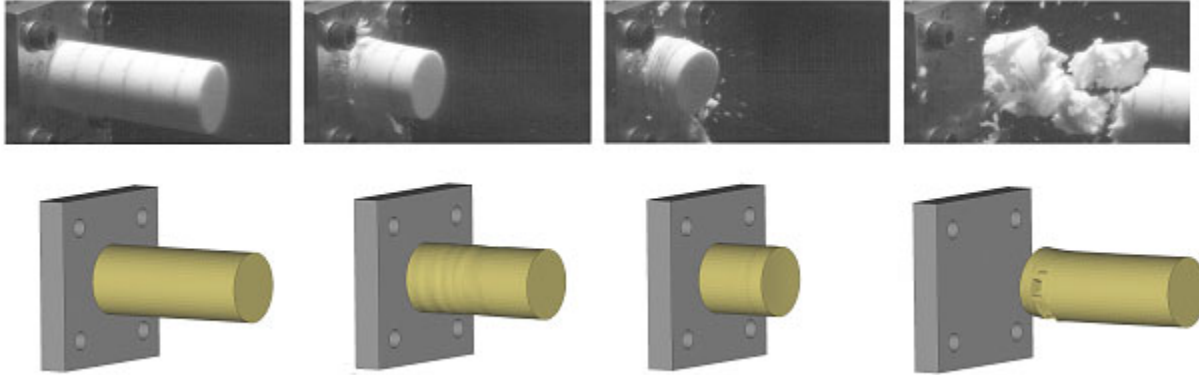


Figure 7. Comparison of foam ballistic impact tests with LS-DYNA predictions.

Once a level of confidence was established with the BX-250 and RCC material models in LS-DYNA, analyses efforts began on the full scale leading edge panels. Results from these analyses were used to support the full-scale test program at SwRI as well as to gain further confidence and validation of our predictive capability. Throughout the investigation, work was continuously performed to understand better, and increase the fidelity of the LS-DYNA predictions. This was done through various means. Reference 4 presents a Monte Carlo method of establishing modeling uncertainties in RCC impact analysis. Reference 5 details the correlation of LS-Dyna predictions with one of the significant tests at SwRI.

The most significant full-scale leading edge test performed by the CAIB was that on Panel 8. In this test, a 1.67 pound piece of foam was shot at 775 feet per second at panel 8. The impact created a hole in the panel sixteen inches square, which can be seen in Figure 8. LS-DYNA analysis predicted a similar hole for those test conditions. This is shown correlated in Figure 9 compared with stills taken from high speed digital photography taken during the test. In addition to the panel 8 test, LS-DYNA was used extensively throughout the full-scale test series to provide assistance in establishing test velocities, projectile sizes, and aim points for each test [6].

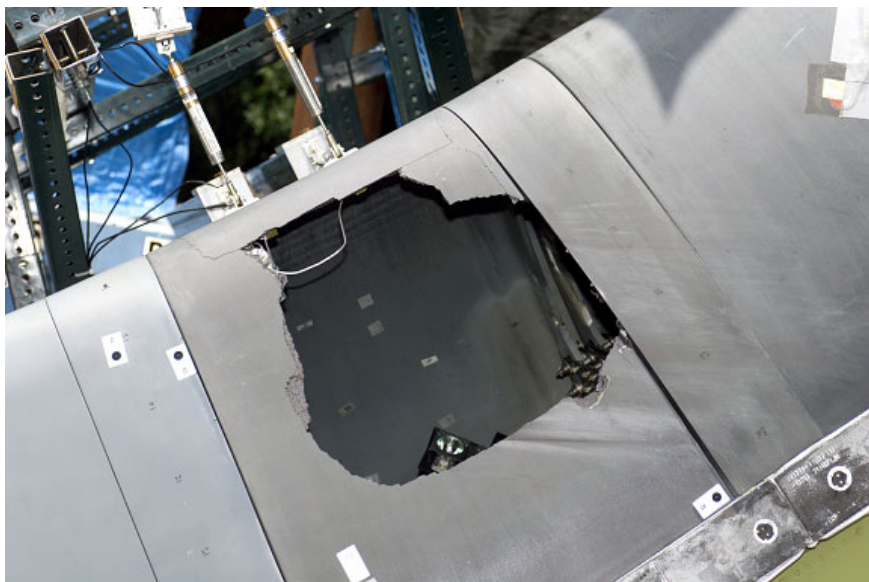


Figure 8. Hole in RCC Panel 8 created by foam impact test at Southwest Research Institute.

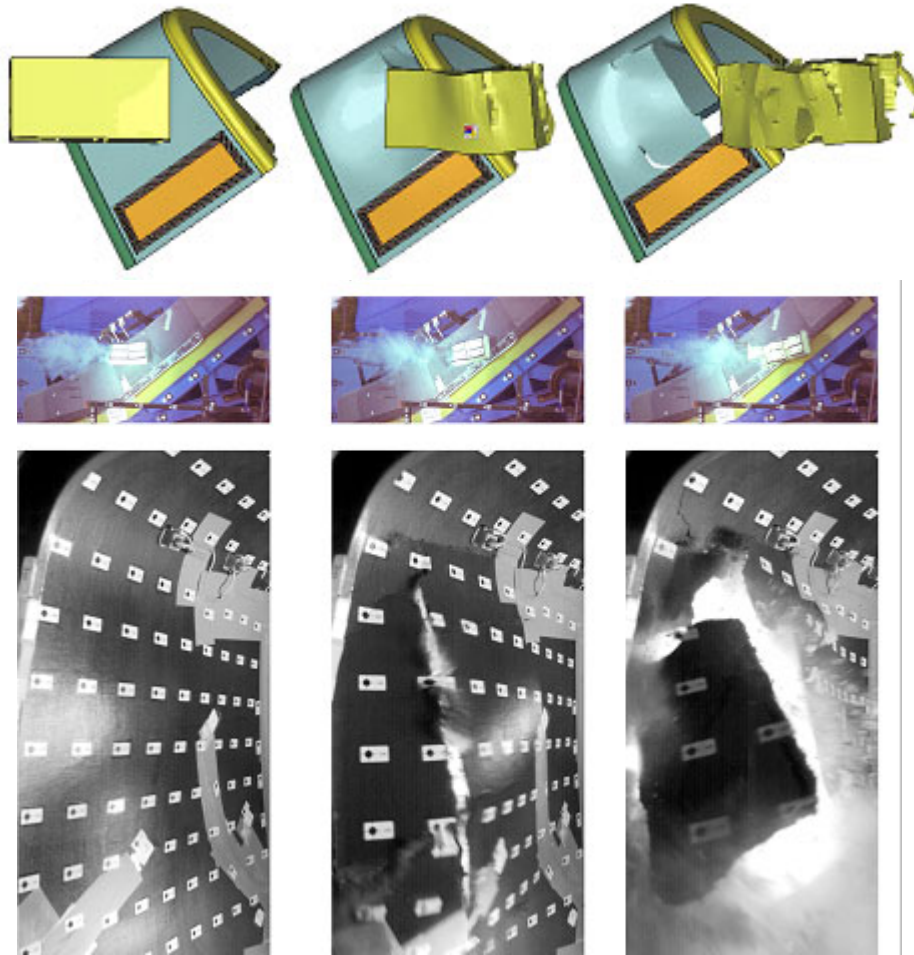


Figure 9. LS-DYNA predictions of Orbiter panel 8 full-scale leading edge test with images from high-speed digital video taken from actual tests.

## Summary

At the completion of the CAIB investigation, an LS-DYNA capability in predicting BX-250 foam impact on RCC material had been developed to a level of maturity highly useful to the Shuttle Program. One of the CAIB recommendations was to “Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts”. Hence, NASA sanctioned follow-on work with LS-DYNA to support the Shuttle’s return to flight. Current efforts underway are the characterization of several other materials that represent potential debris threats to the Orbiter including ice, ablators, and additional foams. In addition, an extensive ballistic impact test program to characterize RCC impact and high strain rate behavior is being conducted to further validate the LS-DYNA predictions.

Shuttle engineers are in the process of defining minimums for any potential debris source based on projectile size, relative impact velocity, and impact location. Hundreds of LS-DYNA analyses will be run to establish the threat for each of these minimums to the Orbiter and its launch components. Should LS-DYNA predict an unsafe flight condition resulting from any given impact, a redesign to reduce the specific minimums further would have to occur before the Space Shuttle returns to flight.

## Acknowledgements

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## References

1. Gehman, H. W., et al, "Columbia Accident Investigation Board," Report Volume 1, U. S. Government Printing Office, Washington, DC, August 2003.
2. K. Carney, M Melis, *et al*, "Material Modeling of Space Shuttle Leading Edge and External Tank Materials For Use in the Columbia Accident Investigation." Proceedings from 8<sup>th</sup> International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.
3. R. Goldberg, and K. Carney. "Modeling the Nonlinear, Strain Rate Dependent Deformation of Shuttle Leading Edge Materials With Hydrostatic Stress Effects Included." Proceedings from 8<sup>th</sup> International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.
4. K. Lyle, E. Fasanella, *et al*, "Application of Non-deterministic Methods to Assess Modeling Uncertainties for RCC Debris Impacts." Proceedings from 8<sup>th</sup> International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.
5. E. Fasanella, K. Lyle, *et al*, "Test and Analysis Correlation of Form Impact onto Space Shuttle Wing Leading Edge RCC Panel 8." Proceedings from 8<sup>th</sup> International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.
6. J. Gabrys, J. Schatz, *et al*, "The Use of LS-DYNA in the Columbia Accident Investigation and Return to Flight Activities." Proceedings from 8<sup>th</sup> International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.