Material Modeling of Space Shuttle Leading Edge and External Tank Materials For Use in the Columbia Accident Investigation

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Abstract

*Upon the commencement of the analytical effort to characterize the impact dynamics and damage of the Space Shuttle Columbia leading edge due to External Tank insulating foam, the necessity of creating analytical descriptions of these materials became evident. To that end, material models were developed of the leading edge thermal protection system, Reinforced Carbon Carbon (RCC), and a low density polyurethane foam, BX-250. Challenges in modeling the RCC include its extreme brittleness, the differing behavior in compression and tension, and the anisotropic fabric layup. These effects were successfully included in LS-DYNA Material Model 58, *MAT_LAMINATED_ COMPOSITE_ FABRIC. The differing compression and tension behavior was modeled using the available damage parameters. Each fabric layer was given an integration point in the shell element, and was allowed to fail independently. Comparisons were made to static test data and coupon ballistic impact tests before being utilized in the full scale analysis. The foam's properties were typical of elastic automotive foams; and LS-DYNA Material Model 83, *MAT_FU_CHANG_FOAM, was successfully used to model its behavior. Material parameters defined included strain rate dependent stress-strain curves for both loading and un-loading, and for both compression and tension. This model was formulated with static test data and strain rate dependent test data, and was compared to ballistic impact tests on load-cell instrumented aluminum plates. These models were subsequently utilized in analysis of the Shuttle leading edge full scale ballistic impact tests, and are currently being used in the Return to Flight Space Shuttle re-certification effort.*

Introduction

One of the key components of any accurate LS-DYNA analysis is the accurate modeling of the material physics. This is particularly a difficult task when failure of the material must be included to accurately represent the system dynamics, and when that failure is a key desired parameter on which to judge the analysis prediction. When ballistic impact analysis is being performed the task can become even more challenging, since the high strain behavior of the material must also be included. The challenges of modeling the materials involved in the Space Shuttle Columbia accident are no exception to these rules [4,5,8].

All of the materials involved in the Space Shuttle Columbia accident are classified as belonging to the Thermal Protection System (TPS) [1,10]. This includes the large piece of foam that broke off from the shuttle External Tank and the ceramic matrix composite that forms the leading edge of the orbiter wing. Prior to the Columbia accident investigation, there had been no explicit finite element analysis performed on any debris impacts, neither impacts that had been observed on the tiles, nor potential impacts on the shuttle leading edge. As a result, no models existed for any of the materials that were suspected as being involved in the accident, or for any other TPS material.

The structural property data available to the analysis was initially limited. Very little relevant structural mechanical property data existed on the insulating foam, as it is not load bearing. Extensive structural mechanical data did exist on the leading edge ceramic composite, but the testing had been performed years earlier, and the old reports were initially unavailable. As a result, the basic physical classification of these materials was initially uncertain. The lack of detailed structural property data did have the benefit of allowing a thoughtful assessment of the material models available in LS-DYNA and their applicability in modeling the physics of the TPS component.

The nature of these materials proved to be challenging to characterize and to analyze. The ceramic matrix composite, which makes up the leading edge, is a Reinforced Carbon Carbon material and is referred to as RCC. The RCC is brittle and stiff; however, it is not particularly strong. The debris that came off of the external tank is low-density polyurethane foam, BX-250. It is relatively soft as compared to the RCC, with a non-linear stiffness. However, it can be strong if highly compressed. The high velocity, ballistic interaction between these two very different materials created contact and material stability problems.

Shuttle Wing Leading Edge

RCC is a material that has thermal properties which make it suitable for the extreme temperature conditions of the shuttle wing leading edge. Its basic structural properties are typical of a ceramic matrix composite. As the name Reinforced Carbon Carbon implies, both the matrix and the fiber are carbon. The material has a 0 degree/90 degree weave pattern and is orthotropic. The properties of the material in its fiber and transverse normal directions are similar. In addition to possessing superior thermal characteristics, RCC is also relatively stiff. However, it is also brittle, and it is not particularly strong.

To protect the carbon of the substrate layers from the atomic oxygen of near earth space the two top and bottom layers of the RCC consist of SiC coating layers. These layers of hard SiCa contain small cracks, which close when the SiC is in compression. As a result, the SiCa layers are very stiff in compression, but can take almost no load in tension. The SiC layers cause the overall behavior of the RCC to be significantly stiffer in compression than it is in tension. An RCC specimen is pictured in Figure 1.

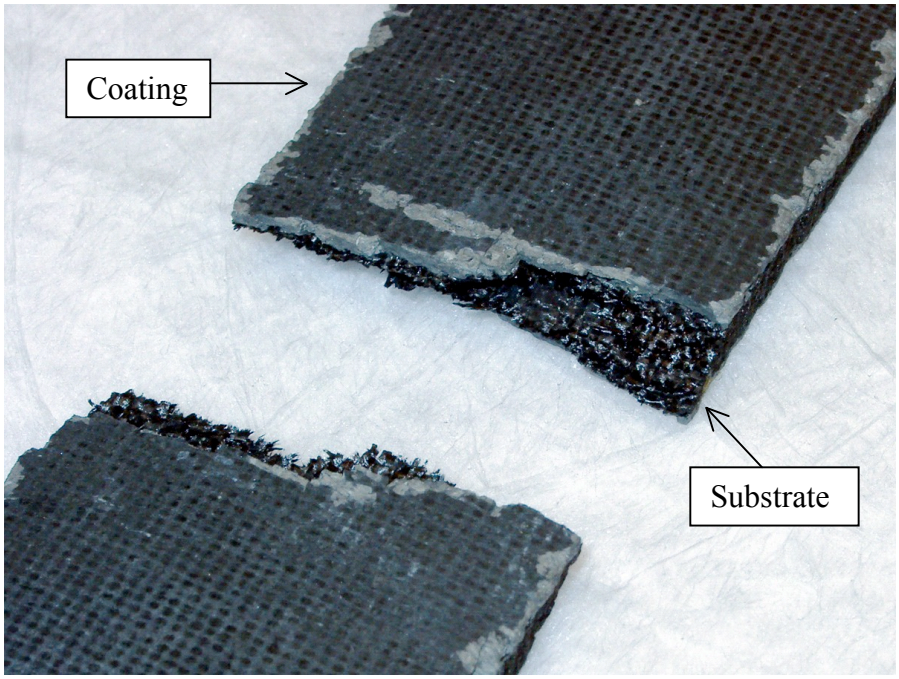

Figure 1. Cracked Specimen of RCC Showing Coating and Substrate Layers.

Including the asymmetric compression/tension behavior is critical to proper modeling of the RCC. The asymmetric behavior shifts the neutral axis when a RCC section is placed in bending. The differing strength in compression and tension also causes asymmetric damage. Although it is not specifically stated so in the LS-DYNA User's Manual, Material Model 58, *MAT_LAMINATED_COMPOSITE_FABRIC, can be used to model this behavior in composite elements [7]. Material Model 58 uses a cumulative damage model created by Matzenmiller, et al [9]. Its implementation in LS-DYNA is discussed by Schweizerhof, et al [11]. The asymmetry is modeled in *MAT_LAMINATED_COMPOSITE_FABRIC by defining the different values for stress and strain at the compressive strength limit and at the tensile strength limit, as shown in Figure 2. The stress-strain behavior of the composite material is then determined by a combination of the damage parameters and the material modulus. The analytical stress-strain curve will be approximate and will not exactly match the physical stress-strain curve.

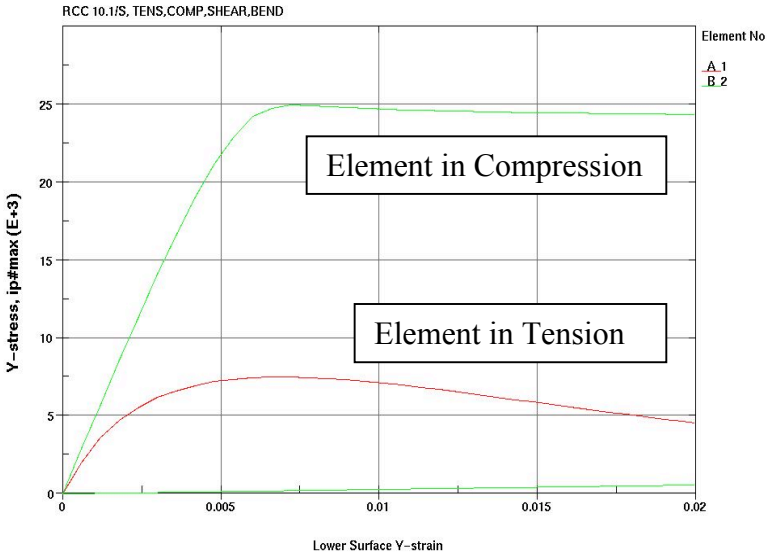

Figure 2. Differing Compression and Tension Behavior of the RCC Model.

*MAT_LAMINATED_COMPOSITE_FABRIC is implemented in LS-DYNA for shell elements. Each layer of fabric, including the SiC layers, is given its own integration point. The Matzenmiller damage model has three non-physical damage parameters, one each for the normal, transverse, and shear directions. As the material undergoes deformation the damage parameters will increase, and it will not unload elastically. Each integration layer has its own damage parameters and so can fail independently, as shown in Figure 3. The element is eroded when its strain reaches a defined maximum, after all its layers have failed. The non-physical damage parameters can be compared with physical damage observed in tests, and so a relation between the analytically predicted damage and actual damage can be established.

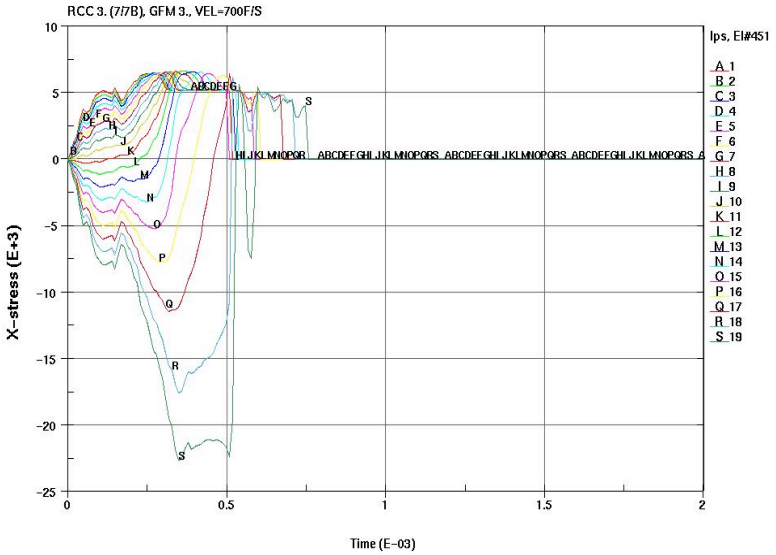

Figure 3. 19 Integration Layers Duplicate Asymmetric Stress Distribution, Failure.

Foam Projectile

The object that struck the leading edge of the shuttle was a piece of low-density polyurethane, closed cell foam, BX-250. As a low-density polyurethane foam, the BX-250 turned out to be very similar to a class of automotive foam. Preliminary ballistic impact tests demonstrated, before any stress-strain data became available, that BX-250 is an elastic foam. With this information, a survey of the relevant material models available is LS-DYNA was performed.

Material Model 83, *MAT_FU_CHANG_FOAM, was determined to be the most appropriate choice for modeling BX-250 [7]. It models elastic foam, and it also allows the user to directly input the complex stress-strain curves with no need for curve fitting. Stress-strain curves at various strain rates can be included in both compression and tension. By including unloading stress-strain test data as the lowest strain rate curve, unloading behavior can be included. It is serendipitous that the Fu Chang foam model, originally developed for crash analysis, turned out to be very applicable to this ballistic impact analysis.

The BX-250 foam is anisotropic due to a directionally elongated closed cell structure, as shown in Figure 4. So called knit lines, which are planes where the cells are smaller, indicate the direction of the cells. *MAT_FU_CHANG_FOAM assumes that the foam is isotropic, and an anisotropic elastic foam model is not currently available in LS-DYNA. Therefore, separate models were created for the maximum strength and minimum strength orientations.

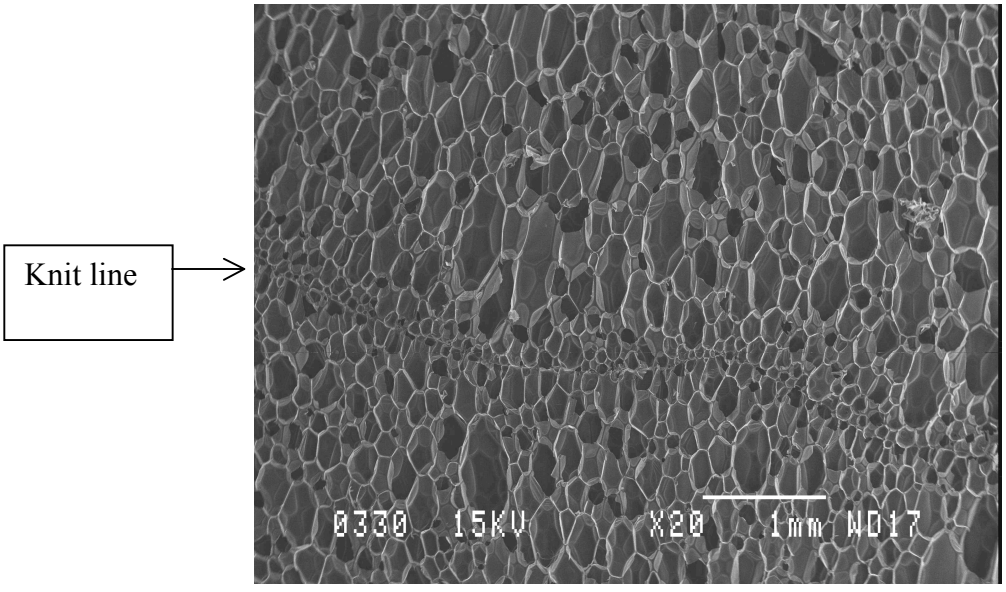

Figure 4. Close-up of BX-250 Foam Showing Cell Elongation and Knit line.

The basic procedure for creating the stress-strain curves for use in Material Model 83 follows references [2,12]. The data curves for the various strain rates must be aggressively smoothed, and formulated with even spacing (one data point per 1% strain is appropriate). The static curve is then extrapolated to very high stress in compression. Additional stress strain curves, for the strain rates data which is available, are then added and extrapolated using the same extrapolation

exponent as the static curve. The unloading curve should be included as the lowest strain rate. Unloading follows the lowest strain rate given in the stress strain curves. The strain rate defined for the static curve can be specified as the low rate at which the static data was actually taken. Tension stress-strain data should also be appended to the compression curves to complete the material definition. Figure 5 illustrates the family of curves input into the BX-250 foam model.

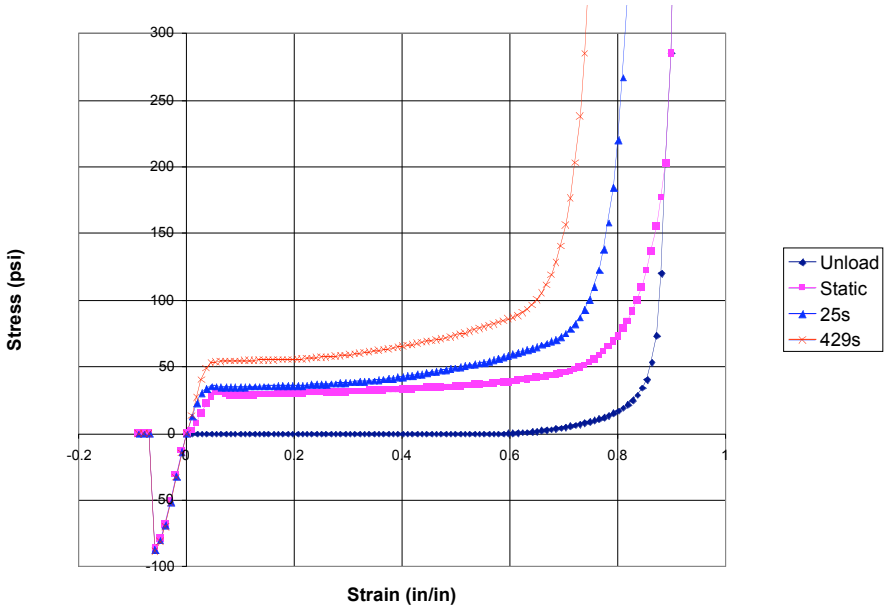

Figure 5. BX-250 Foam Model Stress Strain Curves.

The foam meshes were created using solid elements. Therefore, it was possible to remove foam elements which have failed using *MAT_ADD_EROSION. On the *MAT_FU_CHANG_FOAM card, an appropriate value was given for the tension cut-off stress. Fail Option 1, with the tensile stress being reset to zero when the tension cut-off is achieved, was selected. Both a maximum stress and a maximum strain value were defined on the *MAT_ADD_EROSION card. By selecting the appropriate values, the foam will fail only in tension, using the *MAT_FU_CHANG_FOAM criteria. These failed elements will have their tensile stress set equal to zero, and are eroded when a large strain is subsequently and quickly reached, by the *MAT_ADD_EROSION criteria. Given the potential complexity of erosion in the foam, it is important to include contact of the foam with itself, using a contact definition such as *CONTACT_ERODING_SINGLE_SURFACE.

Data from a series of ballistic tests was compared with analysis using the BX-250 foam model. The ballistic test consisted of shooting a 1.25-inch by 3.00-inch cylindrical projectile onto an aluminum plate, which was instrumented with load cells (See Figure 6). The aluminum plate was oriented at angles of 90, 23, 15, and 10 degrees. The foam projectile, as shown in Figure 7, was shot at approximately 700 and 800 feet per second. The same configuration was modeled in LS-DYNA, with both the projectile and target being modeled by solid elements (See Figures 8-10) and the stiffness of the load cells being represented as springs. Comparing the resulting forces between test and analysis, an example of which is shown in Figure 11, demonstrates excellent agreement. The qualitative behavior of the foam analytical model also showed excellent agreement with high speed video of the test.

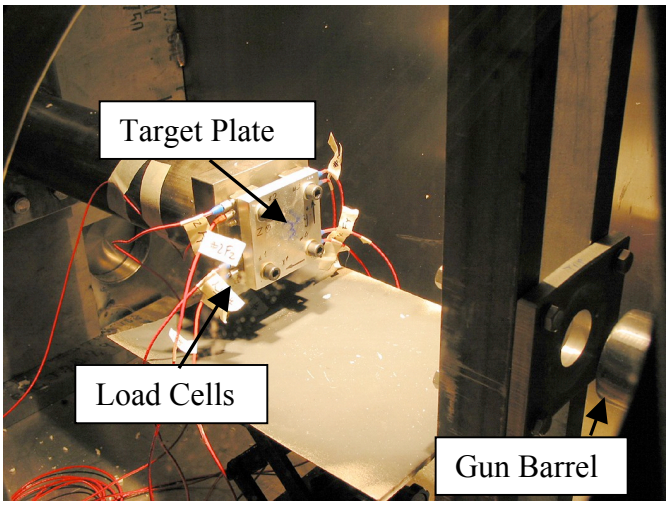

Figure 6. Foam Ballistic Impact Test Setup.

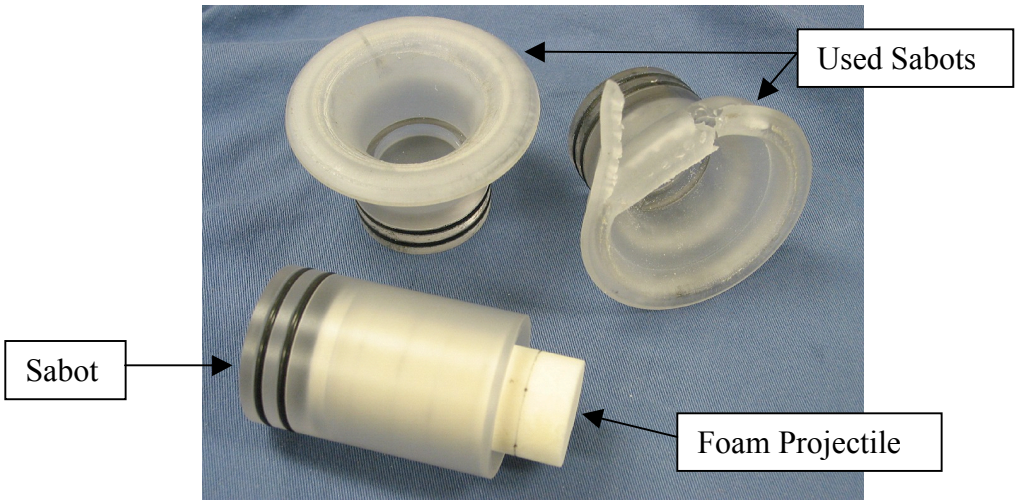

Figure 7. Foam Ballistic Impact Test Specimen and Sabots.

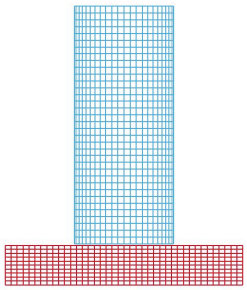

Figure 8. LS-DYNA Model of Ballistic Impact Test, Including BX-250 Foam Model.

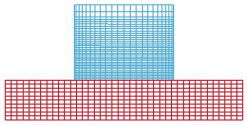

Figure 9. Foam at Maximum Compression.

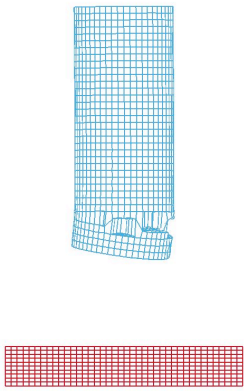

Figure 10. Foam in Final State.

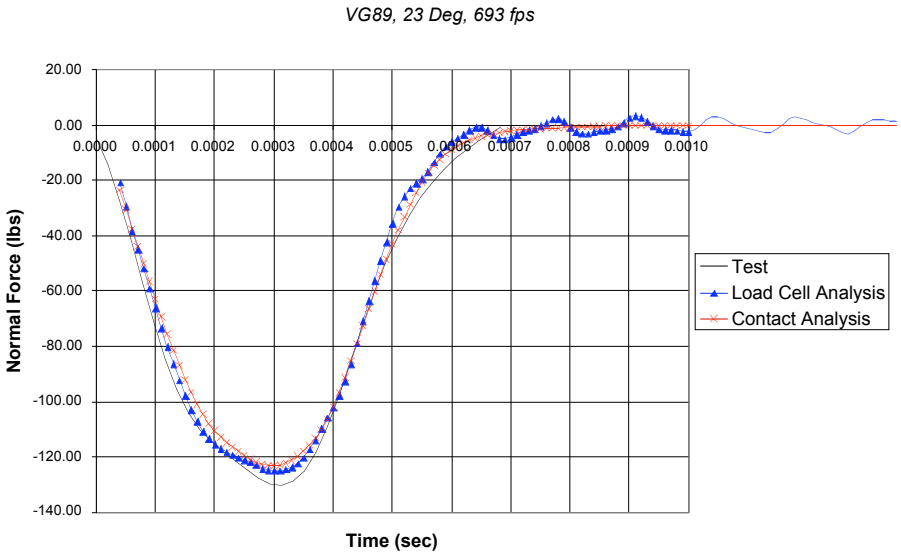

Figure 11. Test and Analysis Comparison for 23 Degree Foam Impact.

Return to Flight

As the efforts of the Space Shuttle program shifted from the investigation of the Columbia Accident, to preparing for the Return to Flight, all potential impact projectiles are being rigorously examined for their potential to cause damage to the leading edge of the shuttle. All materials, which could theoretically fall from the External Tank or other components of the shuttle, including ice, are being tested and their potential velocities are being calculated. In addition, an exhaustive test program is underway for the materials discussed in this paper, in order to complete their physical definition.

Enhancements to RCC modeling that are currently underway include adding strain rate effects to the material model and separately modeling the SiC layers. The test program currently underway has shown that RCC demonstrates a mild, but significant strain rate dependency. LSTC has created a new material model, *MAT_VISCOELASTIC_COMPOSITE_FABRIC, which supplements the equations contained in *MAT_LAMINATED_COMPOSITE_FABRIC, with a viscous stress tensor, based upon a Maxwell model with terms from a Prony series expansion. This new material model is being tested and will soon be available. In addition, a composite material model which intrinsically includes rate effects is also under development [6]. Testing of uncoated RCC has also allowed for direct modeling of the substrate, and for the coating layer properties to be estimated from the combined test data.

Additional materials that are currently being tested and modeled include a crushable foam, which is being modeled using *MAT_TRANSVERSELY_ANISOTROPIC_CRUSHABLE_FOAM, Material Model 142, and various ablators. The ablators are a collection of materials which exhibit viscoelastic behavior, high Poisson's ratios, significant strain rate effects, high damping, and are much denser than the foams found on the shuttle. They are currently being modeled using *MAT_SIMPLIFIED_RUBBER, Material Model 181 [3]. This material model allows the inclusion of the non-linear stress-strain curves directly, strain rate effects and unloading, which are particularly important in viscoelastic materials.

Conclusion

The material models discussed here have been successfully used to model the Columbia Accident Investigation tests, both small and large, which are discussed in the accompanying papers. This work has laid a firm foundation to further efforts which will enable accurate predictions of damage to the shuttle leading edge. A difficult challenge is ahead, in that current program requirements will require the analysis to accurately predict the onset of cracking in just several outer layers of RCC.

Acknowledgements

Many more people were involved in obtaining the excellent test data used than can be thanked here. However, Brad Lerch (NASA GRC) and Sotiris Kellas (NASA LaRC) should be singled

out for working with the analysts to obtain particularly relevant data. Mike Periera, Duane Revilock and Jeffery Hamel (NASA GRC) performed the ballistic impact tests. Ronny Baccus (NASA JSC) uncovered the older RCC data, and is coordinating the current RCC test program.

The creation of these material models would not have been possible without the exceptional support which was given the authors by Paul Dubois, Jim Day, and John Hallquist (LSTC). On multiple occasions, they suspended their other numerous responsibilities to assist us in this important effort.

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