From: "Smith, Jeffrey" <jasmith@sandia.gov>
To: "'Mahendra Shah'" <MJS3@nrc.gov>
Date: 9/3/02 3:41PM
Subject: RE: Material Properties in the Greg Bessette analyses

Mahendra:

Attached is a file that contains a DRAFT of some of the write-up that Greg Bessette is working on. It contains the material properties write-up. In the write-up Greg refers to the aircraft model as a [redacted], I believe it was actually modeled from a [redacted], I have asked him to verify that again. I suspect that within the tolerances of our model it is not a huge difference. Although, I have not had a chance to actually determine the differences between a [redacted]

Ex 2

Ex 2

In regard to the Boeing contract. I just got off the phone with Jerry and he has not been able to find out anything about the Boeing contract. He is trying to get the Sandia Buyer for the contract to contact Boeing to find out what is happening.

I will give you a call in a few minutes.
Jeff

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3.3 CTH Material Modeling

3.3.1 Background – CTH Material Models

The CTH material model inputs for the cask and aircraft are provided in Tables 3-2 and 3-3. The nomenclature in the tables follows the keyword inputs for CTH, which are defined in Table 3-4. CTH model inputs are in cm-g-sec-eV units. The units in the tables have been converted to SI units, as these are more accepted by the engineering community.

CTH decouples the material behavior into the dilatational and deviatoric response. The dilatational response is described by an equation of state (EOS), while the deviatoric response is described by a strength model. In the CTH terminology, the strength model is referred to as an elastic-plastic (EP) model. An EOS expresses a relationship between the thermodynamic pressure, density, and internal energy in a state of equilibrium. An EP model is a plasticity model, designed to capture the shear-induced response of the material.

CTH supports a wide range of EOS and EP models. The choice of model depends on the problem and materials involved. The EOS and EP models used in this analysis are defined in Tables 3-2 and 3-3. The Mie-Gruneisen EOS is commonly used in shock physics applications, and describes the pressure response in the material as a linear function of the internal energy. Porous materials are best represented by a P-α model. The state variable α relates the porous material density to the density of the matrix material, i.e., the void-free material density. It is used to track the crushing behavior of the material. The geologic yield surface allows a pressure-dependent yield surface. The Von Mises yield surface models a rigid, perfectly plastic yield surface. These models are described in more detail in Bell, et. al. (2000) and Hertel and Kerley (1998).

Typically, a fracture model supplements the EOS and EP models. The fracture models in CTH are very simplistic. For this analysis, a PMIN model based on a minimum principal stress criterion was considered. With this model, the material pressure is relaxed to a state prior to fracture whenever the prescribed fracture criterion is exceeded. This is done with an iterative algorithm that increases the material density until a consistent relaxed pressure state is achieved, while holding the energy state constant. Void is then inserted into the cell to account for the change in material volume resulting from increasing the density. The term fracture model is really a misnomer. This model is really a spall model, designed to replicate spallation occurring along free-surfaces.

3.3.2 Cask Materials

Given the time constraints associated with this analysis, heavy reliance was made on using "off-the-shelf" material inputs that would provide a reasonable approximation of the material response. Kipp (2002) provided the baseline material inputs for the cask concrete. This data represents a fit to multi-axis specimen tests of a SAC-5 concrete. SAC refers to the aggregate material, small aggregate chert, and the 5 refers to the 28-day compressive strength of 5000 psi. The 28-day compressive strength of the actual cask concrete is 4000 psi (27.6 Mpa), which is lower than that modeled. Comparable material model inputs were not available for the actual cask concrete. Typically, multi-axis specimen test data is required for the development of the material model inputs.

Preliminary calculations indicated excessive void insertion in the cask concrete due to large tensile stresses being induced in the material. The tensile stress states resulted from stress wave propagating throughout the cask structure and their magnitude was well in excess of the original specified fracture stress. The implications for the PMIN fracture model were unclear. As the fracture stress criterion is exceeded, the pressure is relaxed to a pre-fracture state. The material density is updated so that it is compatible with the relaxed pressure. The change in material density results in void insertion into a cell to account for the more dense material. For spall behavior, this fracture approach is a reasonable approximation; however, here we are dealing with a confined material. Even though the actual material will be pulverized, it still has load-bearing capacity in compression. The excessive void insertion noted in the preliminary calculations was not believed to represent the response of a confined concrete. It was decided to adjust the model to provide a better representation of the response. The adjusted model inputs are shown in Table 3-2.

Another concrete model was also considered and is referred to as the "tuned" model (Crawford (2002)). This model was tuned to match the engine impact experiments conducted by Sugano, et. al. (1993). In these experiments, surrogate aircraft engines were impacted against reinforced concrete slabs. The slabs had a nominal compressive strength of 3700 psi (25.5 MPa) with a reinforcement ratio of 0.4 percent. The concrete model inputs were adjusted to provide a best match to the experimentally observed penetration depths into the reinforced concrete slabs. This model is believed to yield a much stiffer concrete response compared with the SAC-5 model.

Neither concrete model represents the actual cask concrete. Both are expected to reflect a stronger material, with the tuned model being the stronger of the two. Another shortcoming of these models is that neither is capable of assessing the degree of concrete damage. The P-α models do not have any damage parameter, making any assessment of concrete damage qualitative at best. One must bear in mind that we are attempting to obtain global estimates of the cask response. These will serve as initial conditions for more detailed studies seeking to answer the question of cask failure and potential release of radioactive materials.

The steel throughout the cask was assumed to be high-strength steel. At the onset of this analysis, material specifications were not available. Unfortunately, when they did become available, the yield strength of the steel was not corrected. The SA516, Grade 70 steel used in the cask has a static yield strength of 262 MPa and an ultimate strength of 483 MPa at ambient conditions. The dynamic yield strength of the steel will be higher, but still falls below that specified in the problem. The net effect will be to create a stronger cask. The material properties were revised in a later calculation, CTH-SA-REV to better match the actual steel in the cask and assess the implications of using the higher-strength steel. Material input data was readily available for a carpenter electric iron (Johnson and Holmquist (1989)), which appeared to exhibit a comparable hardening response as the SA516, Grade 70 steel. The iron behavior was modeled using a Mie-Gruneisen EOS for iron and the Johnson-Cook strength model. The Johnson-Cook model (Johnson and Cook (1983)) is a phenomenological model that can best be described as an isotropic power-law plasticity model for large deformations. It takes into account both rate and thermal effects. Material parameters for both the EOS and strength model were taken from the CTH material library. The fracture criterion was also modified to match the tensile stress at ultimate failure for the SA516, Grade 70 steel. As will be discussed later, the use of the revised steel properties had little effect on the analysis results. This should not be surprising given the coarse mesh resolution and lack of detail in the cask model.

The multi-purpose canister (MPC) was modeled as a homogenous aluminum body. The material properties were chosen to approximate the mass of the true MPC. The CTH mesh did not have sufficient resolution to model the actual MPC configuration and it was not clear as to how to best model the MPC response in a homogenized configuration.

3.3.3 Aircraft Materials

The aircraft model is a simplified representation of a [redacted] The model developed represents a best estimate of the mass distribution and key hard-points within the aircraft. The stiffness of the aircraft structure affects the loading on the cask. The material model inputs in Table 3-3 were developed to replicate the stiffness of the actual aircraft within the context of its simplified representation. Ex2

There was considerable effort expended to replicate the stiffness of the fuselage skin. The actual aircraft skin has a thickness on the order of millimeters. It is impractical to model a material this thin with CTH, especially given that the mesh must encompass the entire aircraft. An alternative approach was taken to modeling this problem, where the aircraft fuselage was modeled as having an effective thickness with the material properties modified to replicate the stiffness of the actual, ribbed fuselage structure. The modified aircraft material can be described as a "porous" aluminum material. Steve Attaway (2002) describes the development of the porous aluminum material as follows:

" The justification for the "porous" aluminum model was based on an AMR 2D CTH run where a ribbed cross section of an aircraft was meshed with sub millimeter accuracy. This cross section was used as a baseline to compare with the porous aluminum model. The baseline model was impacted into a hard target and a soil target. The material properties for the P-α model were adjusted (within reasonable bounds) to match the momentum-time curve for the ribbed cross-section."

"The underlying assumptions of this method is based on the fact that 95% of the impact force is generated form the change in momentum of material flowing into the active crush

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zone. In the report "Axial Impact Testing of a C-141B Aircraft Fuselage Section with Shipping Containers," SAND94-2739, the velocity of a C-141B fuselage section was plotted as a function of time for an impact with a rigid target at 47 m/sec. The estimated force transmitted from the crush zone to the fuselage was on the order of 1M lbs. This order of magnitude was consistent with a static crush test done at LANL. The crush force of a [redacted] would be expected to be less than the C-141 due to the fact that the C-141 is designed to hall cargo. Reira estimated fuselage crush force to be about [redacted] Ex 2

"Given that the impact force computed from the porous aluminum CTH model for the [redacted] is an order of magnitude greater than the fuselage crush force, the errors associated with the material properties for the P-α model will be small compared to the errors in the location of the mass of the aircraft." Ex 2

"At slower speeds, any error in the crush strength of the fuselage will have a greater effect. There is not doubt that the existing P-α model could be improved. However, before we spend effort to improve this model, a better model of the aircraft is needed."

There was one modification to the porous aluminum material model data. The fracture stress was changed to –1 MPa, an order of magnitude lower than prescribed in the original model. This was done to induce greater break-up of the aircraft fuselage material. As will be discussed in the results section, the aircraft fuselage material appears to be build up in the impact region without any type of fracture or break-up. It was felt that the "cohesiveness" of the fuselage material after impact was unrealistic, as one would expect the fuselage to rupture into small pieces in the impact region.

The porous aluminum material provided a basis for the front wheel section and engine. The aircraft model has a very coarse, homogenized representation of these components, largely due to a lack of detailed structural data for developing a better representation. For example, the front wheel section is modeled as a right circular cylinder. The model does not include the landing strut, its connections to the main body of the aircraft, or the tires. The engine is modeled as a homogeneous component that encompasses the actual engine (compressor, turbine, shaft, etc.), cowling, and wing fixture. Once again, one must bear in mind the goal of this analysis is to assess the global cask response. Here it is important to match the mass of the aircraft components, which in turn, will provide a more realistic assessment of the momentum transfer between aircraft and cask. The material density of the front wheel section and engine were modified to mass-match the component weights. The dilatational response was modeled using a Mie-Gruneisen EOS, using properties from the porous aluminum material. It was unclear as to how to model these homogenized components. These components are significantly stiffer than the fuselage material and it was thought inappropriate to model the material as porous. A simple assumption was made to utilize the same material properties, but consider the material as solid with its dilatational response modeled with a Mie-Gruneisen EOS.

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Table 3-2. CTH material parameters for Cask

Component	EOS Data	EP Model Data	Fracture Model
Concrete (SAC-5 Model) [1]	P-α Model r0 = 2430 kg/m^3 cs = 2550 m/s s1 = 1.24 s2 = -0.001 g0 = 0.1 cv = 86.2 J/kg-K rp = 2240 kg/m^3 ce = 2200 m/s pe = 40.0 MPa ps = 0.75 GPa	Geological Yield Surface Model yield = 0.4 GPa yzero = 10 MPa dydp = 1.32 poisson = 0.226	PMIN, stress pfrac = -1.0 GPa
Concrete ("Tuned" Reinforced Concrete Model) [2]	Mie-Gruneisen EOS r0 = 2250 kg/m^3 cs = 3400 m/s s1 = 1.73 g0 = 1.0 cv = 922.1 J/kg-K	Geological Yield Surface Model yield = 0.5 GPa yzero = 10 MPa dydp = 2.4 poisson = 0.19	PMIN, stress pfrac = -1.0 GPa
Steel Shell, Lid, and Base Plate [3]	Mie-Gruneisen EOS r0 = 7831 kg/m^3 cs = 4651 m/s s1 = 1.37 g0 = 1.67 cv = 460.2 J/kg-K	Von Mises Yield Surface Model yield = 1.43 GPa poisson = 0.30	PMIN, stress pfrac = -1.0e20 Pa
MPC	Mie-Gruneisen EOS r0 = 2710 kg/m^3 cs = 5220 m/s s1 = 1.37 g0 = 1.97 cv = 922.1 J/kg-K	Von Mises Yield Surface Model yield = 0.4 GPa poisson = 0.34	PMIN, stress pfrac = -1.0e20 Pa

[1] Original model inputs for yield, yzero, and pfrac were 0.176 GPa, 0.0 MPa, and –4 MPa, respectively

[2] Original model inputs for pfrac were –15 MPa

[3] Material data corrected in calculation CTH-SA-REV using CTH library data for Mie-Gruneisen EOS and Johnson-Cook strength model for carpenter electric iron. PMIN criteria also changed to –482 MPa.

Table 3-3. CTH material parameters for aircraft

Component	EOS Data	EP Model Data	Fracture Model
Center Fuselage, Wing, Horizontal, and Vertical Stabilizer [1]	P-α Model r0 = 514.42 kg/m^3 cs = 2000 m/s s1 = 1.37 s2 = -0.001 g0 = 1.0 cv = 922.1 J/kg-K rp = 255.3 kg/m^3 ps = 10 MPa	Von Mises Yield Surface Model yield = 7.5 MPa poisson = 0.30	PMIN, Stress pfrac = -1 MPa
Front Wheel Section	Mie-Gruneisen EOS r0 = 1000 kg/m^3 cs = 2000 m/s s1 = 1.37 s2 = -0.001 g0 = 1.0 cv = 922.1 J/kg-K	Von Mises Yield Surface Model yield = 7.5 MPa poisson = 0.30	PMIN, stress pfrac = -10 MPa
Fuel	Mie-Gruneisen EOS r0 = 800 kg/m^3 cs = 1480 m/s s1 = 1.984 s2 = -0.001 g0 = 0.48 cv = 3688 J/kg-K	Von Mises Yield Surface Model yield = 0.0 poisson = 0.50	PMIN, stress pfrac = -10 MPa
Engine	Mie-Gruneisen EOS r0 = 930 kg/m^3 cs = 2000 m/s s1 = 1.37 g0 = 1.0 cv = 922.1 J/kg-K	Von Mises Yield Surface Model yield = 7.5 MPa poisson = 0.30	PMIN, stress pfrac = -10 MPa

[1] Original material input for pfrac was -10 MPa

Table 2-4. CTH material parameter definitions

Material Model	Parameter Definitions
Mie-Gruneisen EOS model	r0 – Initial material density cs – Initial sound speed of material s1 – Linear coefficient in u_s-u_p Hugoniot curve s2 – Quadratic coefficient in u_s-u_p Hugoniot curve g0 – Gruneisen parameter cv – Specific heat
P-α EOS model	r0 –Void-free density for porous materials rp – Initial density of porous material ps – Compaction pressure; pressure at which compaction of porous material is complete pe – Elastic pressure; Used to include an elastic region in pore compaction model, where pe is the minimum pressure at which pore compaction begins ce – Sound speed in elastic pore compaction region cs, s1, s2, g0, cv – same as Mie-Gruneisen EOS model
Geological Yield Surface Model	yield – The yield strength as the pressure becomes very large yield0 – Yield strength at zero pressure dydp – The initial slope of the yield surface as a function of pressure at zero pressure poisson – Poisson's ratio
Von Mises Yield Surface Model	yield – Yield strength in tension poisson - Poisson's ratio
Fracture Model	PMIN, stress – Material fracture with subsequent void insertion based upon a minimum principal stress criterion pfrac – fracture stress of material

3.0 Zapotec Analysis	·

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