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ANALYTICAL AND NUMERICAL MODELING OF GAP FILLER IMPACTS ON SPACE SHUTTLE THERMAL TILES

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The space shuttle is protected during atmospheric re-entry by a thermal protection system comprised of thermal tiles and carbon-carbon materials. To prevent hot gasses from entering the interstices between the tiles, some tiles have a gap filler material placed between them. During space shuttle flight STS-114 (July/August 2005), two gap fillers protruded during ascent. After the safe landing of *Discovery* and before its next flight, a program was begun to understand the mechanical damage to tiles that could result due to gap filler removing itself during flight and striking further back on the Orbiter. Impact tests were performed with gap fillers striking tiles at velocities up to 300 m/s and impact angles up to 20 degrees. An analytical model developed during the Return to Flight program for ice and ablator impacting thermal tile was modified to address gap fillers striking thermal tiles. Fully three-dimensional CTH calculations were performed to study the influence of the shape of the gap filler.

INTRODUCTION

The space shuttle is protected during atmospheric re-entry by a thermal protection system comprised of thermal tiles and carbon-carbon materials. Thermal tiles come in many shapes, but they are typically 15 cm on a side and 5 cm thick. The majority of the Orbiter is covered with these 15-cm square thermal tiles and there is a gap between each tile to allow thermal expansion and flexure of the airframe. The tiles are placed on the vehicle (see Figure 1 for two views of tiled surfaces) and in some cases the manufacturing and assembly process leaves larger than desired gaps between the tiles. When this occurs, a “gap filler” is placed in the space between the tiles to prevent hot gasses from entering the interstices between the tiles. Gap fillers are commonly comprised of an alumina/glass fiber weave in a matrix and are glued in place. To allow for the need to fill different size gaps, the standard gap filler material layer is thin and multiple layers (up to six) are placed between the tiles. In each of the flights since the Return to Flight (after the loss of space shuttle Columbia in 2003), the on-orbit inspection has revealed protruding gap fillers [1-7]. The first Return to Flight mission, STS-114 (July, August 2005), showed two gap fillers protruding after ascent, one of which is shown in Figure 1. The primary concern for protruding gap fillers is that they will lead to an early tripping of the boundary layer during re-entry and thus lead to higher thermal heating during descent. After evaluating the risk of overheating the tiles during re-entry versus the difficulty of removing the protruding gap fillers, an astronaut was sent out on a space walk to remove the two protruding gap fillers. On the subsequent three flights the decision has been to leave protruding gap fillers in place. Figure 1 (right) is a photograph on the ground after re-entry of one of the protruding gap fillers for flight STS-121 (July 2006). The scorch marks on the tile are evident.

Figure 1. Left: protruding gap filler (protruding about 2.8 cm or 1.1”) observed on the underside of the space shuttle *Discovery* as seen from the International Space Station, later removed by an astronaut during a spacewalk (STS-114, photo ISS011e11074); right: re-entry scorch marks on *Discovery* underside near a protruding gap filler on the next flight (STS-121 after landing, author photograph during post-flight inspection).

An additional concern about the protruding gap fillers is that they may detach from the Orbiter and strike further back on the Orbiter either during ascent or re-entry. This event could lead to damaged tiles that could compromise the thermal protection system. After the inaugural Return to Flight, flight STS-114 (July/August 2005), and before *Discovery’s* next flight (STS-121, July 2006), a program was initiated to understand the mechanical damage to tiles that could result due to a gap filler removing itself during flight, being caught in the surrounding flow field, and then striking the tiled surface of the Orbiter. Impact tests were performed with gap fillers striking tiles at velocities up to 300 m/s and impact angles up to 20 degrees. Launching gap fillers is difficult since they are thin sheets that are not very stiff and, in the case of multiple sheets, can separate in flight. Thus they have very unstable flight tendencies. Through unique muzzle modifications and a new sabot design, successful tests were achieved. Experimental diagnostics include high speed video. Figures 2 and 3 show the results of some of the tests. In these tests, three plies (layers) of the gap filler material were used for the impactor. The large deformations the gap filler material can undergo are evident. Also evident is that, though these gap filler materials might be viewed as flimsy, they are able to damage the thermal tiles. Damage depends on orientation at impact.

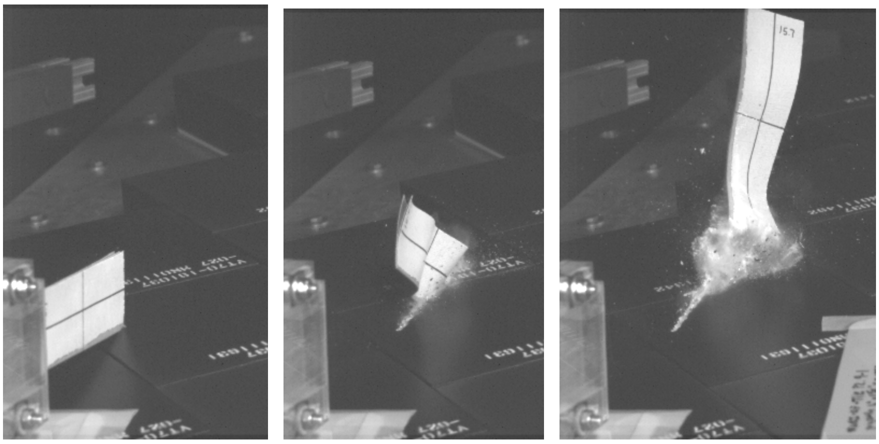

Figure 2. 3-ply gap filler striking thermal tile: impact speed 56 m/s, angle 10.1 degrees (Test 2.9-3).

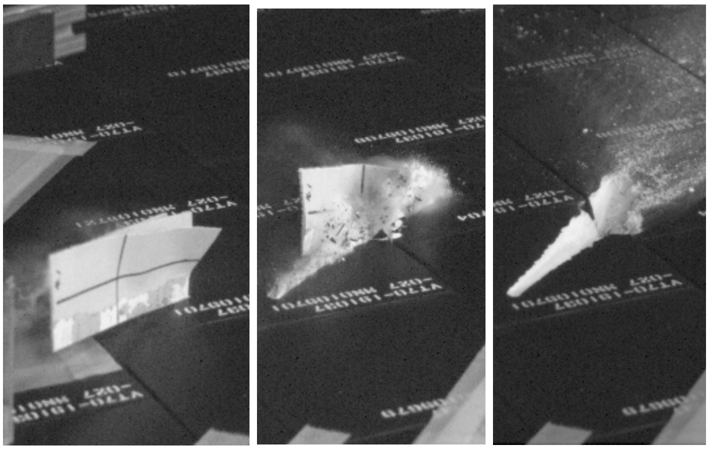

Figure 3. 3-ply gap filler striking thermal tile: impact speed 182 m/s, angle 10 degrees (Test 1.5-2).

Fully three-dimensional CTH computations were performed to study the influence of the shape of the gap filler and its impact orientation. These type computations had previously been performed for ice and foam impacts into thermal tile to better understand the role of impactor shape, orientation and rotation [1,3,4,7-9]. In the foam impactor situation, such computations were particularly important due to the difficulty of launching unusual pieces of foam. The difficulty for foam arises from the fact that the material density is so low that sabots are not used – rather the foam fits the barrel. Thus, given the experience with foam and ice impact into tile, a similar approach for the computations of gap filler material striking tile was taken. Three different configurations were studied: edge impacts, flat impacts and impacts with the projectile angled (rolled) at 45 degrees. All the configurations produced similar damage in the tiles although the rolled gap filler was slightly more severe.

The testing and modeling supported the development of an analytical model that was used by the space shuttle community to estimate the risk to the space shuttle caused by gap fillers detaching and striking the vehicle further aft. These risk estimates were incorporated into the total risk estimates for flight.

MATERIALS

The majority of the experimental results were based on impacts of 3-ply ceramic Ames gap fillers. The nominal density of the material is 1.6 g/cm^3 (100 lb/ft^3). The nominal size of the 3-ply gap fillers that were tested was 15.24×4.92×0.13 cm (6×1.9375×0.052 inch) for those impacted in the edge orientation and 15.24×4.92×0.10 cm (6×1.9375×0.041 inch) impacted in the flat orientation. These gap fillers struck the LI-900 thermal tiles. Brief descriptions of the two materials are given in Table 1.

Table 1. Materials

Material	Nominal Density (g/cm^3)	¨Modeled¨ Density (g/cm^3)	Brief description
LI-900 HRSI	0.18	0.18	Black tiles, density 9 lb/ft^3, thick protective glass layer
Gap filler	1.6	0.36	Nextel AB312 Alumina-Borosilicate-Fiber in ceramic matriz

ANALYTICAL MODEL AND RESULTS

In order to perform the risk assessment, a fast running model of the gap filler impact into tile was needed, a model that provided the resulting damage (crater) depth, length and width information given the impact speed and impact angle. The space shuttle program had already baselined models for the impact of ice and ablator materials into thermal tiles [1,10]. It was felt that the development of a new model for the gap filler impacts would take considerable time due to the geometric complexity of the impact event (see Figures 2 and 3), and so the program decided to pursue a modification of the ice and ablator into tile impact model inputs to reflect the behavior of the gap filler material.

The ice and ablator models are physics-based models, and as inputs require the geometry of the impactor, impactor density, thermal tile material crush-up table, and impact speed and angle. The model has been baselined for ice, low density ice, and ablator material impacting specific thermal tile materials, but since the model is based on first-principles physics, it should be possible to use it since the material properties of the impacting gap filler material are known. In fact, using the direct density and geometry of the gap filler does produce a worst-case impact, where the gap filler strikes edge-on and for the most part maintains its shape during the impact event. However, the actual impact event does not show such behavior by the gap filler, but rather the gap filler deforms and opens up during the impact, thus effectively reducing its density while increasing its size. By comparing the model output with the impact test data, the following procedure for using the ice-into-tile impact model was developed to reproduce results of 3-ply gap filler impacts into LI-900 HRSI tile. In particular, the nominal curve was based on values that have 50% of the impact crater depth data above the curve and 50% below. The 95% bounding curve is such that 95% of the impact crater depth data lies below the curve. The modifications are

1) For the nominal crater depth and length values, use the nominal ice-into-tile impact model but reduce the density of the gap filler material by a factor of 4.5 while increasing the impactor width by a value of 4.5. This change maintains the mass of the impactor but decreases the density to 0.36 g/cm^3 (0.22 lb/ft^3) and changes the dimensions of the impactor to 15.24×4.92×0.59 cm (6×1.9375×0.234 inch). The experimentally determined value of 2.54 cm (1 inch) is the crater width, rather than the value returned by the model.

2) For the 95% bounding curve, use the 95% bounding ice-into-tile model but decrease the gap filler density by a factor of 3.0 and increase the width by a factor of 3.0. This change also maintains the mass of the impactor but decreases the density to a value of 0.53 g/cm^3 (33 lb/ft^3) while changing the dimensions of the impactor to 15.24×4.92×0.40 cm (6×1.9375×0.156 inch). The gap filler height of 4.92 cm (1.9375 inch) is the crater width, rather than the value returned by the model. The 95% bounding curve in the ice and ablator into tile impact model is obtained by reducing the pressure in the tile density-pressure crush-up table pairs by a factor of 0.615. This value was obtained by comparing the model to extensive ice impact data. Since the model is physics based, the only option for adjusting its output is to adjust the material properties that are input, and so the 95% curve is obtained by softening the tile.

The above dimensions were based on the edge impactor geometries. For the flat orientation impacts, a width of 0.10 cm (0.041 inch) was used so that the flat geometry after adjustment was 15.24×0.47×4.92 cm (6×0.185×1.9375 inch) (nominal) and 15.24×0.31×4.92 cm (6×0.123×1.9375 inch) (95% bounding).

The above adjustments were baselined by the program for use for 3-ply gap filler impacts. Baselining is the procedure used to verify and validate a critical math model in the space shuttle program. In this case, the model was already verified since the same software was being used as was previously baselined for the ice-into-tile model. The input adjustments led to comparisons with the data to then validate the model for use in gap filler-into-tile modeling.

Figure 4 (left) shows the gap filler-into-tile model and its comparison to data. The lower curve is the “nominal” depth of penetration given by the analytical model, the upper curve is the 95% confidence curve which, through a material strength reduction, encompasses 95% of the experimental data, and the points are impact data points. The usage is as described above.

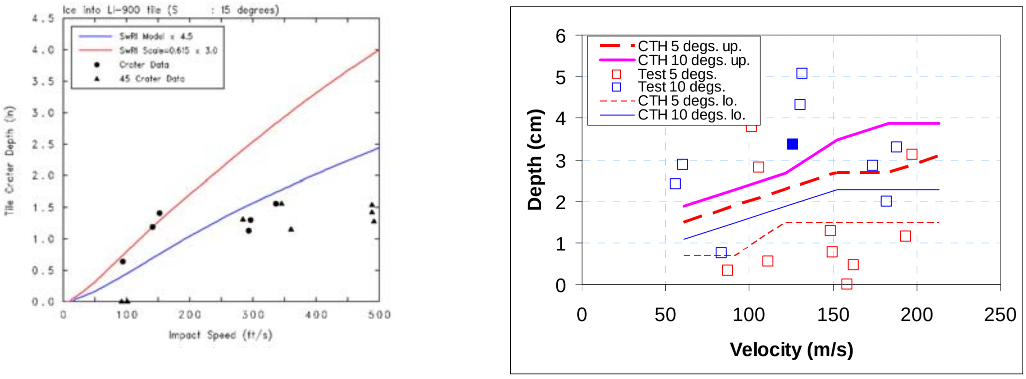

Figure 4. Gap-filler impacting LI-900 HRSI tile. Left: comparison of analytical and experimental results for a gap filler impacting at 15 degrees at different velocities; right: comparison of computations with CTH (lines) and tests (symbols) at 5 and 10 degrees. The full symbol indicates a 45 degrees roll impact.

CTH COMPUTATIONS

The gap-fillers are too narrow to resolve computationally as is, since their width is 0.10-0.13 cm (0.041-0.052 inch) and typical cell sizes in the Eulerian impact calculations are on the order of 0.4 cm. Thus, a similar approach was used to model the gap filler in the CTH computations as in the analytical model: to have a reasonable computation time (around 12 hours) the “numerical” gap-filler used was artificially thickened to 15.24×4.41×2.41 cm (6×1.74×0.95 inch). To keep the mass of the gap filler the same (17.5 g or 0.039 lb), the density was decreased from 1.6 g/cm^3 to 0.108 g/cm^3. The cell size of Eulerian mesh used in CTH was 0.4 cm. Where possible a plane of symmetry was used. Figure 5 shows views of computations. For the 45 degree roll of the gap filler, no symmetry existed and a full tile array was modeled (left image).

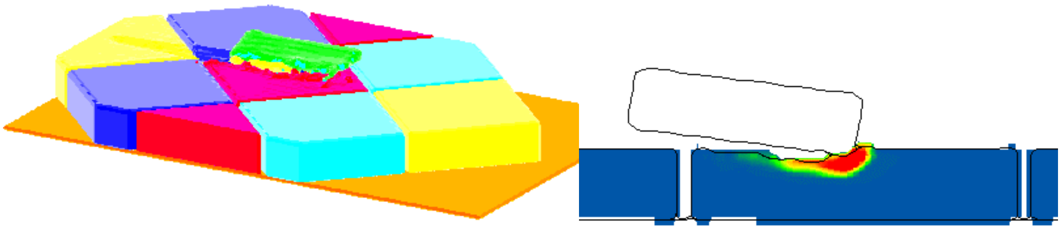

Figure 5. Left: CTH computation with the gap filler rolled 45 degrees; right: edge impact of gap-filler into tile showing densification or crush-up of the tile. The region of tile directly under the gap filler impact point has a density of 1.9-2.0 times the original density of the tile.

The constitutive model of the gap-filler was an educated guess. The bulk sound speed was assumed to be 2 km/s, the slope of the particle velocity vs. shock velocity was assumed equal to 1, and a Grüneisen coefficient equal to zero was assumed. The strength, a simple von-Mises plasticity model, was taken to be 10 MPa. All these computations were performed without the “slide” option in CTH.

The foam model used for the tile allows irreversible densification of the tile when it is in compression [3,7,9,11]. In addition to the tile material’s ability to crush up, it can also fail and not be able to support shearing stresses though it still supports compressive stresses. In the right of Figure 5 shading shows the extent of tile material permanent crush-up. The crushed tile material shows as different shading depending on the amount of permanent compaction.

When measuring the depth of penetration in the computation there are two approaches to take. The first is to consider the crushed tile material (above a certain density, typically 200% of the initial) as part of the crater: since it is failed material it will exit the cavity at some point and so should be considered part of the crater. The extent of the tile material that is crushed to failure provides an upper bound on the depth of the crater. The other approach is to say that the failed tile material is part of the tile since it was not displaced by the actual impact, so the crater extent should only be the region where material was removed by the actual impact event in the computation. This view provides a lower bound for the crater size. Both options are shown in Figure 4 (right) for impacts at 5 and 10 degrees and velocities from 50 to 250 m/s. The thick lines are the upper bound while the thin lines are the lower bound. CTH overpredicts the crater depth for impacts of 5 degrees. As an aside, if CTH’s “slide” option is used the computations, in general, underpredict the results.

When dealing with gap-fillers the scatter in the data is large so matching with CTH is only qualitative. These runs are performed to compare crater depth and geometry produced by different impactor geometries, something an analytical model cannot easily do.

CONCLUSIONS

The ice-into-tile impact model developed for the space shuttle program was extended to use for gap filler impacts into thermal tiles by experimentally determined adjustments to the material property and impactor geometry inputs. CTH computations were performed that matched well the experimental and analytical results in a large range of velocities, angles and orientations, giving a high degree of confidence in the reliability of the results.

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