Conf-950582--1

SAND94-2324C

STRUCTURAL ANALYSES OF THE JPL MARS PATHFINDER IMPACT*

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Abstract

The purpose of this paper is to demonstrate that finite element analysis can be used in the design process for high performance fabric structures. These structures exhibit extreme geometric nonlinearity; specifically, the contact and interaction of fabric surfaces with the large deformation which necessarily results from membrane structures introduces great complexity to analyses of this type.

All of these features are demonstrated here in the analysis of the Jet Propulsion Laboratory (JPL) Mars Pathfinder impact onto Mars. This lander system uses airbags to envelope the lander experiment package, protecting it with large deformation upon contact. Results from the analysis show the stress in the fabric airbags, forces in the internal tendon support system, forces in the latches and hinges which allow the lander to deploy after impact, and deceleration of the lander components. All of these results provide the JPL engineers with design guidance for the success of this novel lander system.

Introduction

The exploration of Mars includes a survey by a small instrument laden lander, called the Mars Pathfinder, for initial definition of the Martian environment. Ths program, managed by the Jet Propulsion Laboratory, calls for the lander to impact on the surface using a parachute retarding system and a bridle mounted retro-rocket system to slow down and orient the airbag protected lander. The airbags are designed to protect the vehicle by limiting not only contact with the surface, but also the decelerations of the vehicle. This type of landing precludes the use of a much heavier, complicated, and expensive actively controlled rocket system normally associated with this type of landing.

The Pathfinder lander is a tetrahedron structure with three articulated 'petals' which are used to right the structure onto its base, the fourth petal. An airbag is connected to each of the four faces of the tetrahedron at six corner locations with tethers. These tethers run across the outside of the airbags through the troughs formed by the bag intersection to a central cusp; penetrating through the central cusp, they continue inside the airbags and connect to the six lander corners by penetrating the airbags and joining with the exterior tethers.

The Pathfinder lander will deliver an instrumention package and robotic rover to the surface of Mars. Acceptable deceleration loads and protection of these packages are the prime design parameters for JPL. The design of the airbag system is of vital importance for the success of the mission. This paper describes the structural analyses of the various parts of this system which were used in support of this design process. Explicit finite element analyses of the impact were completed for a variety of impact orientations and surface roughnesses. These analyses determined fabric stress in the airbags, loads in a variety of internal tethers used to maintain shape, and accelerations of various portions of the lander itself.

Details of the very complex geometry and analysis technique are presented, along with representative results and comparisons with scale model tests. All of these results show how structural analysis can be used in the design of high performance fabric structures.

*This work was performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

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Analysis Methodology

The analysis of a large membrane structure impacting a surface is inherently nonlinear, especially when the structure is composed of airbags laying on top of each other. The only way to effectively model a structure of this type is with an explicitly integrated finite element code. Because of the stable shell/membrane contact experience with ABAQUS/Explicit [1], this code was used for the analysis. Due to the complex geometry of the bag design, the mesh was created using Patran [2]. These are the tools used to define the analytical model.

The design of the bags is such that there is substantial interference between the neighboring bags prior to inflation. During inflation, the bags come to equilibrium by laying on top of each other. The areas of contact between the bags is a function of the bag geometry, fabric stiffness, and the pressure used to inflate the bags. Also, internal tethers are used to provide support for the lander, while providing shear reactions to the lander for an oblique impact. The initial overlapped airbag shape produces preloads in the tethers. The tether force and relative angle to the lander can only be determined with a nonlinear finite element model of the system.

Producing the initial inflated shape is the most challenging part of the analysis. A technique had to be devised whereby this initial geometry could be defined.The JPL design of the airbags is a combination of intersecting spheres protecting each face of the lander tetrahedron. The airbags on the adjacent faces overlap, thereby protecting the 'gaps' between the airbags. This overlap causes great difficulties in producing the finite element model of the Pathfinder system; and is also of extreme importance in producing the correct preloads in the membrane of the airbags and the tethers.

The airbags had to first be physically separated to remove the interference between the bags. This is due to the contact algorithms used in finite element analysis. (only small overlaps can be corrected with ABAQUS/ Explicit without changing the geometry of the airbags). Once the overlap is removed, the contact identification could then be turned on locally between the airbags. At this point, the airbags were then reinflated.

The airbags achieve an equilibrium state after re-inflation. Because the thin shell elements are now in a stable, well formed state, global contacts between the complete airbags can now be turned on (local surface contact was used for the preliminary re-inflation). The contact algorithm recognizes that a complete volume is defined, and a robust set of contacts are possible for the subsequent impact with even a rough, penetrating surface.

The implementation of the technique is described below.

Analytical Model Description

The finite element model in the 'as designed' state is shown in Figure 1 (the view uses a cutting plane to show the inside details of the model). The overlap in the 'as designed' model is clearly visible in the figure. At this point, a velocity boundary condition is applied to the sphere centerpoints of each airbag to uncover the airbag interference. This state is shown in Figure 2 (because an elastic material behavior is used, this extreme deformation does not affect the final stress state in the airbags).

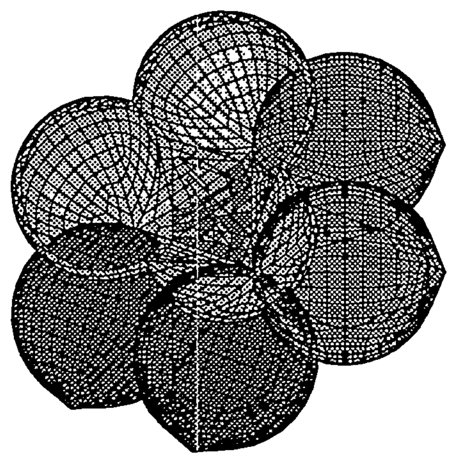


Figure 1. Overlapped Finite Element Model of Lander

At this stage in the analysis, the contact surface definition is initiated so that the local area of interference recognizes the position of its opposing surface, and a boundary condition is now imposed by the analysis code to prevent penetration. As the bags are then reinflated using internal pressure, they lay on top of each other in the state of equilibrium between the airbag pairs. This equilibrium state is shown in Figure 3, again using a cutting plane to view the inside of the airbags.

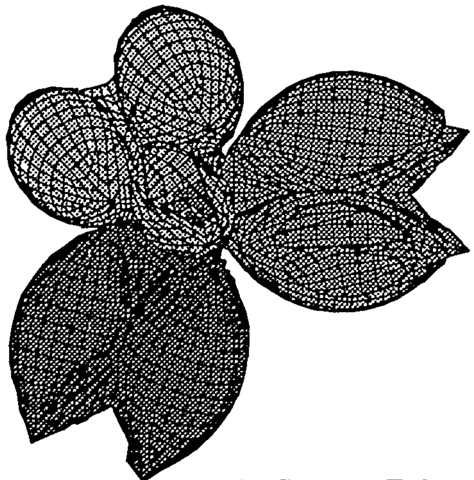


Figure 2. Lander Airbags with Clearance Enforced

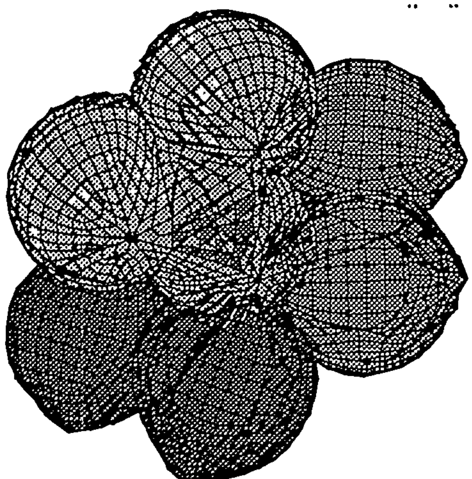


Figure 3. Airbags After Re-inflation and Contacts Defined

Only the shell elements local to the zone of interference are used for this initial contact definition. As the actual impact occurs, gross bag-to-bag motion and interaction will occur, as well as bag penetration for the rough surface impact; therefore, a more robust contact is desired for the final analysis step. Because the elements are well shaped after re-inflation, a robust contact definition is now possible. This new contact definition takes advantage of the volume treatment which ABAQUS/Explicit uses for a closed volume (local penetration which causes surface normal reversal does not confuse the contact set). This robust contact will be illustrated in the results portion of this paper. Complete volume sets defined by the entire airbags are now initalized, which now makes the rotating lander/impact surface contact possible.

A body acceleration field is used at this point to produce the velocity of impact (generally this step occurs over 10 msec; a body or gravity loading is used to prevent stress buildup in the respective portions of the structure). At the end of this analysis step, the body or gravity loading is reduced to simulate the gravity of Mars.

Material Behavior

The data used to define the material behavior was determined from high strain-rate testing of parachute materials [3]. For Kevlar, the airbag and tether construction materials, the strain rate sensitivity is not very great. Strain-to-failure of 5% was used for all analyses. Data from the same reference shows that negligible temperature effects occur in Kevlar, so the exact temperature of the deployment does not affect the material response.

Thin shell elements were used for the analyses. These were used to assist with the stability of the contacts. The bending terms with materials which are 0.004 in thick are very small, but not zero. Fabric made of Kevlar also has some finite bending stiffness, so this approximation is felt to be appropriate.

Testing in the high altitude chamber at Sandia [4] showed that the actual pressure-time-history during the impacts did not vary greatly. The actual time of contact is ~ 40 msec, so a great amount of gas flow between the airbags is not expected. Using this information, a pressure loading inside the airbags was used for the structural analysis and is appropriate.

Analysis Cases

Four analyses were chosen by JPL to envelop the range of stresses and loadings for the Pathfinder lander. These were 1) vertical impact onto a smooth surface at 20 m/sec, 2) oblique impact at 20 m/sec vertical and horizontal velocity onto a smooth surface, 3) oblique impact onto a rough surface (0.5 m tall 'rocks'), and 4) oblique impact onto a smooth, 30° inclined, surface.

For all of these analyses, the time-history results for deceleration of the lander, tether loads, hinge and latch forces, and fabric stress were determined. Only one analysis will be described to accomplish the purpose of this paper; the oblique impact onto the rough surface provided an excellent example of the nature of the structural analysis of the Pathfinder lander.

Test Validation

Testing at the Sandia Coyote Canyon Test Facility [4] of a scale model (.38 scale factor) was used to validate and calibrate the analytical model shown earlier. Primarily, the maximum deceleration and pressure were used to refine the analytical model.

The test chosen for the validation is the vertical impact test case. This test had the smallest deviation from an impact normal to the surface. Peak deceleration of 20 g's (total vector sum) was measured from this test. The internal pressure during the test was 1.2 psig. Deformation of the finite element model at the peak deceleration time of 22 msec is shown in Figure 4.

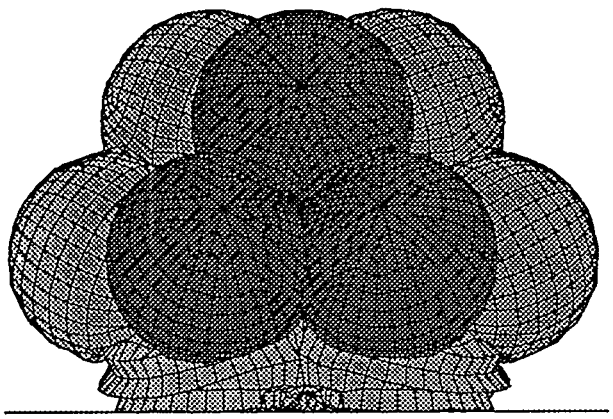


Figure 4. Maximum Deformation from Vertical Impact Analysis for Validation with Test

Placing this internal pressure inside the analytical model and simulating the impact velocity, a net acceleration of 22.5 g's was produced. Several parameter studies were performed on the model and the following information was determined: 1) Moduli of the fabric (within the range of experimental error for Kevlar) did not have a great effect on the deceleration, 2) the internal pressure of the airbag system defines the deceleration of lander system, 3) tether forces are dependent on the initial pressure, and causes an effective stiffening of the lander system, i.e. tethers raise the peak deceleration by causing greater surface area to be engaged more quickly in time.

The analytical model was found to be approximately 15% 'stiffer', or had a slightly higher peak deceleration during the impacts. This is due to the mesh chosen for the model, and this effect is visible in the deformed mesh plot shown in Figure 4. A certain amount of 'wrinkling' occurs in the mesh at the contact line with the surface of impact. Because this mesh dependent 'wrinkling' occurs at the maximum radius of the airbags, the surface area of contact, and thereby the deceleration, is dependent on the mesh chosen for the analysis.

It is not surprising that the results from an analysis of this type would be mesh dependent, given the direct coupling of geometry/pressure to the results (finite element results are normally stiffer than the actual response). The most important point to be learned is that the results are now verified with test data (similar results were also found for higher speed tests). Knowing that the analytical response is slightly stiffer validates the model as a design tool. These results are slightly conservative for the primary design quantity, the maximum deceleration of the Pathfinder lander.

An additional result used to validate the model was surface friction between the impact plane and the Kevlar airbags. Virtually no relative motion was observed between the impact surface and the airbags during an oblique impact test. To prevent motion in the analytical model, a coefficient of friction of 2.0 was required. This value seems high and unrealistic, but is in reality a function of the contact surface between a rigid and a very flexible surface. All the oblique analyses completed here used this coeficient of friction.

Now that the model has been validated, the analyses of the four impact cases were completed. Results for one of the analysis cases are presented below.

Rough Surface Oblique Impact Results

The finite element model used for the impact of the Pathfinder onto a rough surface is shown in Figure 5. The 'rocks' used for the analysis are 0.5 m in height, and were formed by raising the center node of the initially square grid to the height described by JPL. The Pathfinder was accelerated until it achieved the 20 m/sec horizontal and 20 m/sec vertical velocity. The internal pressure used for this analysis was 1.2 psig.

The sequence of motion shown in Figure 6 shows the action of the impact during 80 msec of time (each frame is 20 msec increments of time). The nature of the impact is visible in the sequence of scenes; as the rocks trap the airbags, the lander rolls over onto other rocks until the

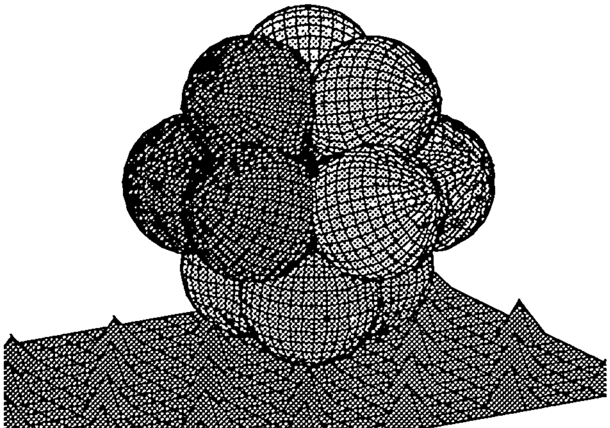


Figure 5. Finite Element Model Used for Oblique Impact onto a Rough Surface

velocity is reversed. The rocks cause the lander to recover at a higher angle than the incident angle. This is due to the blunt angle of attack which the vertical surfaces of the rocks present to the airbags. The peak deceleration of the impact was 23 g's horizontal, and 30 g's vertical for a net of 38 g's. The complete acceleration time-history is shown in Figure 7.

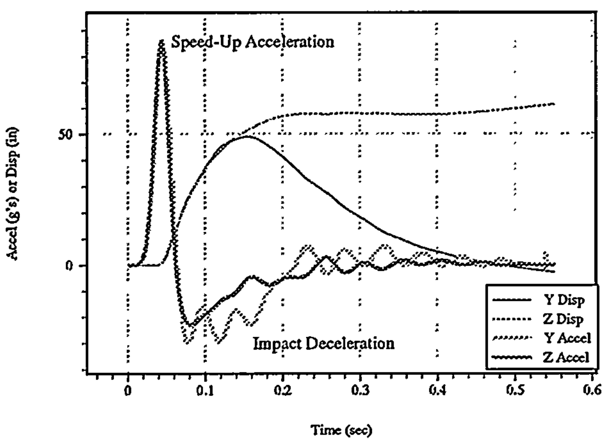
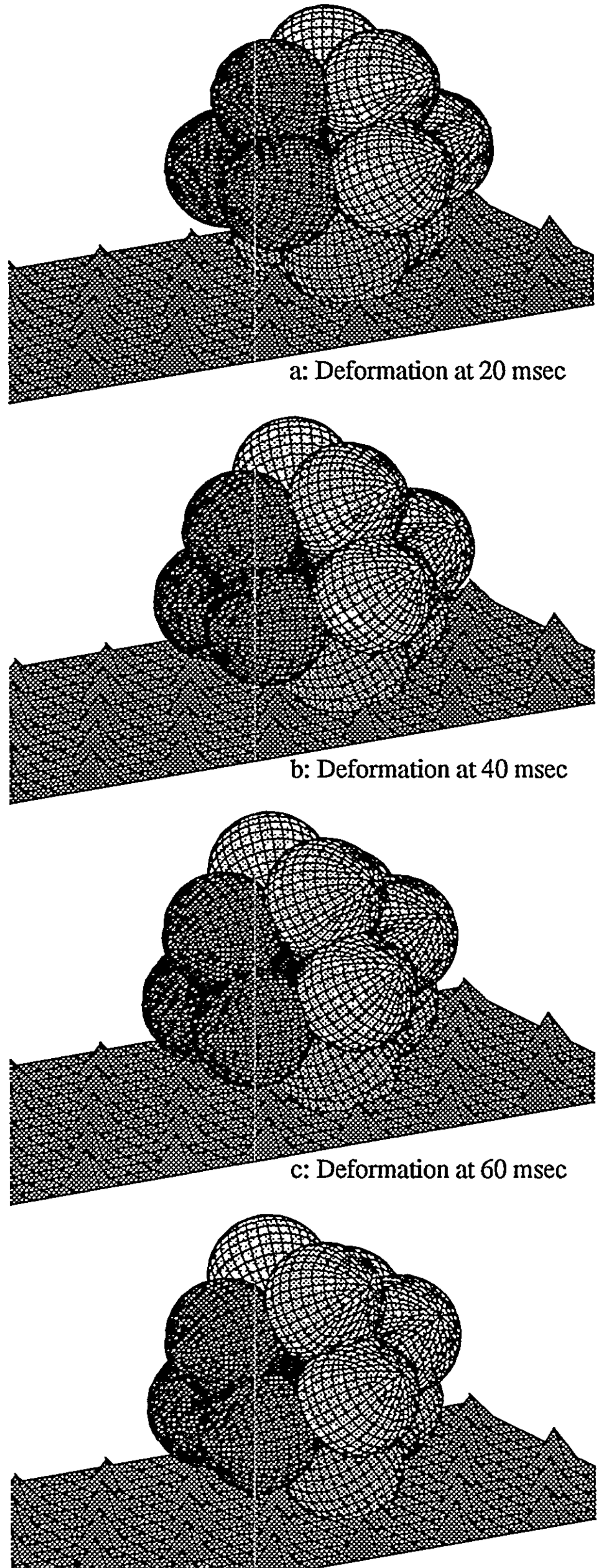


Figure 7. Acceleration Time-History of Rough Surface Impact

The blunt angle which is presented to the lander also has an effect on the fabric stresses. A view of the bottom airbag from inside the lander is shown in Figure 8 (a cutting plane is used to remove the top portion of the model for clarity). The protrusion of the rock tip is visible in the plot. This is due to the way that contact algorithms detect intrusion. As a node crosses through the plane defined by the shell elements, a restoring force is used to push the nodes back. Because the rock rigid elements are defined by a single top node and the base nodes, some penetration is expected since the height is greater than the airbag elements characteristic length. This has a



a: Deformation at 20 msec

b: Deformation at 40 msec

c: Deformation at 60 msec

d: Deformation at 80 msec

Figure 6. Oblique Impact Onto a Rough Surface - Deformed Mesh at 20 msec Increments

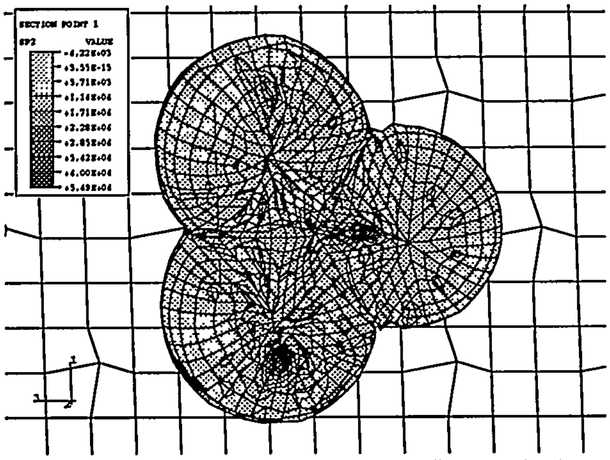


Figure 8. Fabric Maximum Principal Stress Distribution for Bottom Airbag at 25 msec

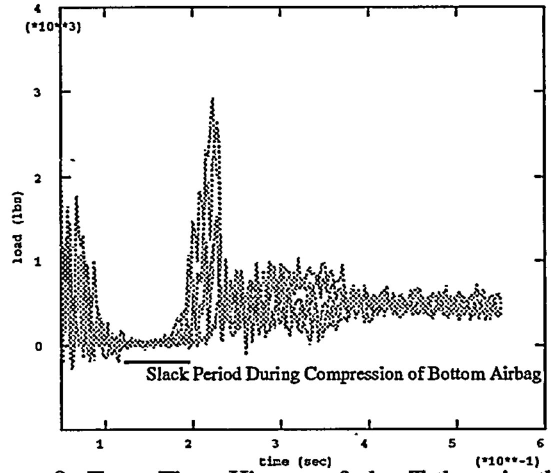


Figure 9. Force-Time History of the Tethers in the Lander During Impact

net effect of 'rounding' of the rock peaks (which were obviously arbitrarily formed).

Also shown in Figure 8 is the maximum principal stress distribution for this point in time, 25 msec. This is the point when the maximum deceleration occurs. The maximum stress found in the analysis is approximately 40,000 psi. Since the fabric thickness used in the analysis was 0.0105 in, the required fabric strength for this impact condition is 420 lb/in (thickness multiplied with the stress). As a general rule, fabric stresses one element away from the contact point are reported so no anomalies will be introduced.

The forces in the tethers during the impact are very interesting. As the bottom airbag is compressed, the preload in the tethers goes to zero. As the impact continues, the airbag contact area and the corresponding recovery forces increase, pushing back on the lander. Since the collision is elastic, the bottom airbag is restored back to its initial size, which reloads the internal (and external) tethers of the impact airbag. Corresponding to the change in geometry of the bottom airbag, the top airbags experience additional contact with the bottom airbag. Any change in geometry from the initial equilibrium position requires additional forces. This is evident in the tether forces and the fabric stresses in the top airbags. Force-time histories of the tethers in the lander system are shown in Figure 9.

It is evident from Figure 9 that the internal tethers go slack during the impact, and reload after re-expansion of the airbags (as noted in the figure). Also, as the bottom tethers go slack, additional force is required in the top airbags. The highest tether forces are found in the front-most airbag, which receives the greatest shearing load. A peak force of 4,000 lbs was found during the impact for this airbag, which determines the required capacity of the internal tethers. The dynamics of the airbags are also evident from the force-time histories. Vibration of the airbags causes some oscillation during the impact event.

A view inside the lander shows the action of the various components during the impact. This is shown in Figure 10, where a cutting plane is used to provide this view.

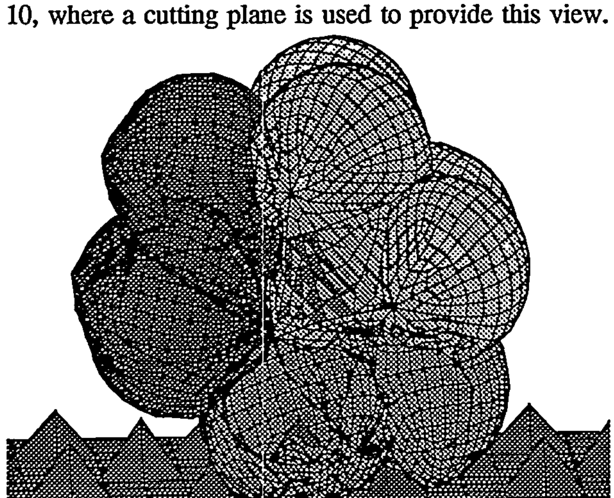


Figure 10. Inside View of the Lander During Impact

The bottom airbag tethers are slack, and the front airbag is starting to shear over the top of the impact bag.

Forces at the hinges and latches are also required for designing these components. The time-histories of force for these components are shown in Figure 11. Because

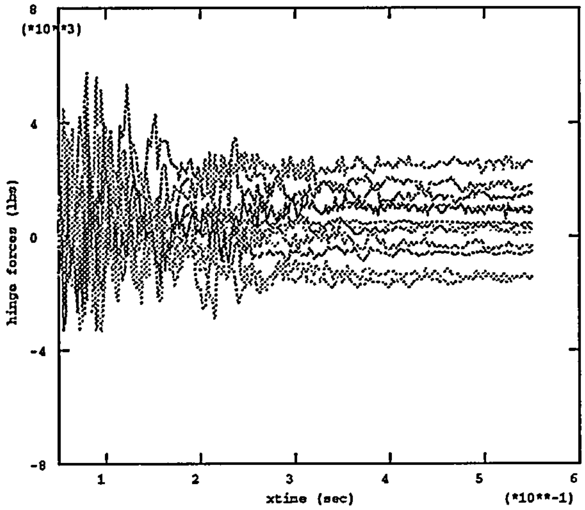


Figure 11. Hinge Force Time-History for Impact

nodal constraints between the appropriate degrees-of-freedom were used to connect and restrain the lander petals (i.e. an element was not used to model these components directly), stress/area in the connection region is used as the method to report these forces. Forces normal to and perpendicular to the lander edge are reported.

Discussion of Results

Two interesting points have been learned from this analysis. First, the initial overlapped geometry produces zones where excess fabric exists, and membrane action for load transfer is therefore not very efficient . It essentially takes more fabric, and weight, to produce a shape that is less structurally efficient. Designing the airbags to reflect these zones of interference would make the system lighter and more efficient for load transfer.

Secondly, the internal tethers cause a high stress zone to exist where the bags are pulled into the center, as shown in Figure 8. If the tethers were longer, the airbags would be allowed to expand, thereby reducing the membrane load required to pull them to their present position. This would reduce the current stress state in the fabric. Also, the pulling of fabric into the middle causes more airbag area to be encountered in a shorter period of time. This raises the deceleration of the lander. Letting the airbags expand would reduce the deceleration, while adding to the distance between the impact plane and the lander.

Conclusions

Deformations, and therefore the stresses, of airbag systems from impact at high speed cannot be reduced to a 'simple' system of linear responses. The nonlinearities due to bag-to-bag contact, large rotation and deformation, as well as complex impact conditions require analyses with the tools described here. The explicit finite element analysis of this lander has been used to determine the acceleration of the lander, fabric stresses, hinge and latch forces, and tether forces for this very complicated system. A greater understanding of the load distribution in the system is now known, and design factors-of-safety can now be determined.

Finite element analyses of this type are very useful for determining not only the gross responses of this type of system, but also the local design parameters of components.

Acknowledgments

Tom Rivellini, JPL, allowed this analysis technique to be developed while under the time constraints of a flight program, and his initiative and patience during this process is greatly appreciated.

Kurt Metzinger, a colleague in the Materials and Solid Mechanics Department at Sandia, was invaluable in assisting with the setup of the contacts in the analysis. The author acknowledges his contribution to this program.

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