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Airbags to Martian Landers - Analyses at Sandia National Laboratories*

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Abstract

A new direction for the national laboratories is to assist U. S. businesses with research and development, primarily through cooperative research and development agreements (CRADAs). Technology transfer to the private sector has been very successful as over 200 CRADAs are in place at Sandia. Because of these cooperative efforts, technology has evolved into some new areas not commonly associated with the former mission of the national laboratories. An example of this is the analysis of fabric structures. Explicit analyses and expertise in constructing parachutes led to the development of a next generation automobile airbag; which led to the construction, testing, and analysis of the Jet Propulsion Laboratory Mars Environmental Survey Lander; and finally led to the development of CAD based custom garment designs using 3D scanned images of the human body. The structural analysis of these fabric structures is described as well as a more traditional example from Sandia with the test/analysis correlation of the impact of a weapon container.

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Introduction

Many changes have occurred in the way the national laboratories are 'doing business'. As the cold war draws nigh, a new mission of the labs is to transfer technology into the private sector to aid U. S. industrial competitiveness. To accomplish this heretofore prevented commercial cooperation, a new law allowing the DOE laboratories to enter into cooperative research and development agreements (CRADAs) is now in effect. To many in the weapons complex, this is viewed as an erosion of the noble defender of the nation status; to others, the change is a wonderful opportunity to assist industry by blending the national labs research and development expertise with the focused needs of industry. At Sandia, almost 200 CRADAs are currently in place. The reason for the success of these CRADAs is the cooperative aspects of the agreement. The role of the industrial partner is to insure that the developed product or technology will be useful (either in the short or long term) and that the development will occur in a timely and efficient fashion. The laboratories role is to use our R &D expertise in computation/test correlation and our test facilities in helping solve some of the nations industrial problems. The industrial partner must provide in-kind funding to assure that the development doesn't occur in a vacuum. The goal is to improve national competitiveness by 'giving back to the people' some of the research and development investments that the labs incurred over the past 40 years and use the labs as a newly available national resource.

As these CRADAs continue to evolve, technology transfer has brought the labs into some very new directions. What will be presented here are some examples from the Engineering Sciences Center of how this technology transfer is working. One specific example I have worked on is the new field of fabric structures. There has been a direct progression from the analysis of high performance parachutes - to the design of the next generation automotive airbag - to the analysis of an airbag protected landing of the Mars Environmental Survey vehicle - to the garment industry in providing optimized designs using 3D descriptions of people in producing 2D fabric patterns. Also shown are some more traditional examples of Sandia's expertise; analyses to support the design of weapon transport containers for protection in various accident environments. Most of these analyses used the explicit analysis techniques in ABAQUS/Explicit [1], primarily because of the large motions during inflation and the contact algorithms necessary to understand these structures. Analytical pre- and post-processing used Patran [2].

Fabric Structures Analyses

The analysis of a variety of fabric structures has proved challenging. These structures include parachutes of various geometry, next generation automobile airbag design, Martian landers protected by encompassing airbags, and recently fabric being draped over a human body for the CAD design of custom garments. Frequently, just setting up the initial state of these analyses can be the most challenging part. Modeling the equilibrium state of airbags laying on top of each other is difficult because the geometry of this state and the initial stress of the material is radically different from the "known" construction of the structure. Then the challenge of initializing the pressure in a membrane structure, which has no stability when unloaded, and keeping the contact algorithms from blowing the structure apart until it has enough stiffness to come to equilibrium has proven to be interesting, to say the least. Finally, the dynamic contact of what is an inherently pliable material with various underlying supports (or sometimes no support at all like a parachute unfolding) is sometimes the least challenging part of the problem, as long as you can hold your breath long enough.

Several examples of these fabric structure analyses are described in the following sections, along with the problems and solutions involved.

Martian Lander Analysis

The exploratic of Mars includes a survey by small instrument laden landers for initial definition of the environment, called the MESUR program run by the Jet Propulsion Laboratory. The program calls for the impact of several landers on the surface using a parachute retarding system to slow down and orient an airbag protected lander on the surface. The airbags are designed to protect the vehicle by limiting not only contact with the surface, but also the deceleration of the vehicle. This type of landing precludes the use of a more sophisticated "controlled" landing using the much heavier and much more complicated retro-rocket systems normally associated with this type of landing. Once the lander is stopped, the articulated petals of the tetrahedral lander will unfold, righting the vehicle in the process and ultimately uncovering the various instruments for the survey operation. Vents allow gas to pass between the bottom airbag and each of the top airbags as a pressure difference occurs during landing, allowing a softer effective impact. Obviously, the design of the airbag system is of vital importance for the success of the mission. Validation of the analytical model uses 38% scale model tests (tests completed at the Sandia Coyote Canyon Cable Facility); once this validation is completed, the extension to the Mars design is possible.

The design prediction of the fabric stress in the airbags, the capacity of various internal tendons used to connect to the lander to these airbags, the stress in the hinges of the petals, and finally the acceleration time histories at the various instrument locations is the goal of the analysis. A view of the external geometry of the lander system is shown in Figure 1. Four large airbags are connected onto each face of the tetrahedral lander. Each airbag consists of three intersecting spheres which are constructed of kevlar fabric. In the external valley of each intersection runs a kevlar strap, which all intersect at the center point and penetrate the airbags. Each tendon continues to the inside corners of the lander body. As each airbag is inflated, a contact zone is formed between each of the airbags. An initial analysis step is required to form these contacts.

Each of the airbag membrane geometries are defined (and built) to form independent shapes (Figure 2 shows an internal view with the interference visible). The extra material formed by the intersection with the adjacent airbag is gathered into the contact zones, which forces the tendons to carry the majority of the preload to the lander surface. Because the initial equilibrium state depends on the flexibilities of various components, the initial configuration cannot be predetermined and an analysis step is required. To accomplish this, the contact element sets (which define the contact between each of the airbags) are first used to apply pressure and push the airbags back until there is no interference. At this point the contacts are turned on, and the internal pressure is applied. This forces the airbags to lay on top of each other and come to equilibrium before the impact occurs. It was found during the course of the analysis that the internal pressure must be applied as an impulse to keep stability of the airbag elements. A slow pressure application was first used, but since no tension exists in the elements (and very little pressure is required to initially move the airbags) the contact algorithm overwhelms the element motion. Using an impulse to load the internal pressure seems to load the elements both with its own inertia until the internal pressure is high enough to maintain stability of the membranes. Generally, an anneal step is required after the impulse to quiet down the oscillatory motion of the airbags since little damping exists in the model. The internal geometry of the lander system is again shown in Figure 3, which shows the lander, the internal tendons, and the airbags now in the overlapped condition.

After the initial airbag overlap is defined the actual analysis can begin. Because of the anneal steps, no initial stress or initial velocity conditions are possible, so acceleration must be used to achieve the initial velocity of the impact. A body acceleration using the gravity option is used to get the lander up to the initial impact speed, generally 80 m/sec. A large body loading is used to accelerate the lander to this speed in 10 msec. Prior to impact, the gravity of Mars (38% of Earth's) must replace this body loading which requires another step. Five analysis steps later the problem is ready to start.

To define the pressure/volume relationship between the airbags, the vent area is used along with an adiabatic expansion definition to relate the pressure change in the top airbags with the volume change in the bottom airbag [3]. The instantaneous pressure of the airbags are defined with the airbag elements and the ABAQUS/Explicit capability to provide the current volume to a user defined expression (otherwise this exercise would be very tedious). The use of this expression also allows the difference between the Earth validation tests and the Martian atmosphere to be incorporated (Mars atmosphere is approximately 0.1 bar, which greatly affects the volume/pressure relationships).

Various impact parameters that include lateral and horizontal velocity along with the angle of the ground and the roughness of the ground were completed. A sample of the results are shown in Figure 4 which steps through several analysis times for a 25 m/sec horizontal and 20 m/sec vertical impact velocity. Friction is used between the airbags and the surface to cause rolling of the lander (which is the prime function of the tendons). A plot of acceleration vs. time for the lander center of gravity is shown in Figure 5 for these conditions, and the maximum principal stress in various internal components is shown in Figure 6 for the highest stress condition. It is obvious that many of the capabilities of ABAQUS/Explicit were required for this analysis to succeed.

Cross Parachute Analysis

Another problem with initial geometry was encountered with the coupling between a computational fluid dynamics code (CFD) and ABAQUS/Explicit. The initial steady state shape is required to complete the CFD analysis, but the shape is also dependent on the resulting structural response of the pressure distribution. A simple iteration scheme was devised using ABAQUS/Explicit and the CFD code Rampant [4]. The parachute model is constructed as flat panels which cross in the center. The warp runs down the long axis of the membranes. The pressure behind a Mach 3 bow shock was applied to the model and the dynamics of "filling" the parachute were analyzed. After approximately 50 msec the dynamics of this filling process had reached a reasonably quiet state, and the deformed shape was then passed through Patran to Rampant to more accurately analyze the complex flow and pressure distribution through the parachute. The flow vectors from the CFD analysis are shown in Figure 7, and the resulting pressure distribution used for the final structural analysis is shown in Figure 8. Flow accelerates in the corners of the parachute, where the pressure is low, and the stagnant zone in the center builds to the maximum pressure found. The double material in the center of the cross produces a flatter shape than was predicted by parachute designers, and also causes a different flow field and pressure in the center of the parachute.

The more detailed pressure distribution and temperature field from the CFD analysis was then used in a final structural analysis to determine the stresses in the suspension lines and the parachute canopy, which is shown in Figure 9. The intent of the analysis was to determine the maximum altitude that the parachute could be deployed and still survive the flow field. Stresses in the canopy, and also the suspension lines, were low enough that the kevlar fabric would survive. The deformed shape using the more detailed CFD pressures distribution was not significantly different from the free stream approximation, used to initialize the CFD analysis. If significant differences had been found, another round of analyses using the updated shapes would have been completed. This analysis showed that the simple coupling technique used here between the CFD and the structural analysis was very useful in determining what would have been practically impossible to test and document. A gridless CFD/2D structural coupling development, which provides a much greater coupling between the two analysis techniques, is currently underway at Sandia; the demonstration of the value of the solution shown here was important to proving the value of this kind of solution.

Automobile Airbags

Sandia is involved with a CRADA to develop the next generation airbag for automobile use. Expertise in the design, testing, and production of parachutes led to the development of the CRADA. Many tests of candidate materials and shapes were completed in the Rapid Inflation Facility at Sandia, which uses high pressure air from the wind tunnel facility to simulate the airbag inflation. Analysis of the many tests proved invaluable in determining fabric design, seam locations, and ultimately the minimum required strength for a new material to succeed.

Taking a 2D material, and forming a 3D pressure vessel in an efficient manufacturing manner, as well as maintaining efficient structural performance, is not easy. The airbags now in use utilize two flat circles sewn around the periphery. The resulting shape in not optimized because the seams must necessarily cross the weak locations of the fabric (the bias strength of a fabric is frequently 20% of the warp direction) and the shape does not approximate a sphere for optimum structural performance.

Airbags are generally built of at least 420 denier nylon. The inflation of the airbags occur in approximately 10 msec, so an investigation of the strain rate effects of the material was initiated. High strain rate testing at the Sandia Livermore, CA facility, which tested the material to strain rates of 10 in/in/sec (corresponding to the strain rates obtained from the analytical model), showed an approximate 30% gain in strength over the slow rate test results. Because of this result, a more complete investigation was completed at the extreme temperatures for airbag systems, and at room temperature for a variety of candidate fabrics. These tests were then modeled with ABAQUS/Explicit to insure that the material behavior used in the modeling was adequate.

The various combination of tested material properties, repeatable pressure, high speed video coverage for analytical comparisons, has led to the successful completion of the next generation design. This design is currently being marketed and details of this airbag design will be forthcoming as the CRADA partner completes this portion of the agreement.

Fabric Draping for the Garment Industry

An interesting extension of the technology developed for the airbag and parachute analyses is the use of structural analysis in the design of custom garments. In a CRADA with Clarity, Inc., we are coupling CAD tools with garment design experience and explicit structural analysis to produce custom garment patterns for a variety of products. The same difficulties of a 2D fabric being used to produce a 3D product described before are also present in the garment industry. The goal of this development is to overcome these draping difficulties, taking into account gravity and the fabric streching, and to introduce new technology that uses the digital scan of the human body as the basis to directly produce a custom garment.

Clarity, Inc., has developed a technique which uses the CADDS5 software of ComputerVision and the rules of tailoring to produce a "fabric abstraction" of the finished garment. Using a digital scanned image of the body, fabric is pieced onto the body using standard practice of garment design, but the question is always "how will it lay on the person?". Of more importance is, for a stretch fabric which has very low stiffness in one direction, how can we optimize the fit or comfort of the garment?

The role of using structural analysis to optimize the design of garments is a new one, to say the least. When the fabric is abstracted from the 3D scanned image, the analysis takes the faceted garment design, and places loads (gravity, straps, etc.) on the fabric structure. This now allows the fit to be optimized by using pressure in the body underneath, and actually allows for the measure of comfort. The design can be altered at this point until the pressure is evenly distributed, or until the desired draped shape is produced, after which the fabric can be relaxed to an unstrained state. This optimized shape is passed back to the fabric abstraction design so the unstrained pattern can be mapped onto the 2D state. This process places structural analysis as a valuable participant of the computer aided design cycle of custom garments.

A demonstration of this fabric abstraction is shown in Figure 10. The digital model of a standard dress form with a garment laying on top is the basis for the analysis. ABAQUS/Explicit is used for the analysis because of the complex and continuous contact of the dress form underneath. The purpose of this model was to demonstrate the information flow between the various partners.

Reentry Vehicle Transport

In a more traditional example of Sandia's original mission, the protection of weapons during transport must be proven for safety of the public and the assets involved with the weapon itself. Reentry vehicles (the prime payload of intercontinental ballistic missiles) are primarily shipped via truck in the continental United States. Shipping containers are designed to survive accident conditions which might be present during transport. An example of such a container is shown in Figure 11, which shows the reentry vehicle support on a foam lined support structure. Dropping the container at 400 in/sec on its end is the analysis described here.

The container uses very soft foam, which does not damage under high strain and the analysis used the hyperelastic foam model recently implemented into the explicit version of ABAQUS. A multitude of contact conditions were modeled between the various components of the model and the initial velocity was used to load the model. Acceleration of the internal components was used to validate the analysis with testing completed at Sandia. The maximum deformation found from the analysis is shown in Figure 12. The foam compresses to a strain of approximately 65% during the event. Analytical accelerations are compared with those from testing, where reasonable comparisons were found for this event. Analyses of this type are useful for determining the efficiency of the container design, and the protection available from more extraordinary events. Higher velocity impacts showed some stability problems when the foam was compressed to very high strains (approaching 100%), and an orthotropic foam crush model implemented in PRONTO3D [5] was required for these higher speed impacts.

Conclusions

The examples shown here describe how the ABAQUS/Explicit code has been used in the analyses of atypical structures, specifically those which are constructed of fabric. As this field continues to develop, structural analyses of objects which have no inherent structure will continue to push the explicit analysis technique into some very interesting applications. The nature of explicit analysis allows for this flexibility.

Acknowledgments

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[5] PRONTO 3D, A Three-Dimensional Transient Solid Dynamics Program, Taylor, L. M., Flanagan, D. P., SAND87-1912, Sandia National Laboratories, Albuquerque, NM, 1989.

Figures

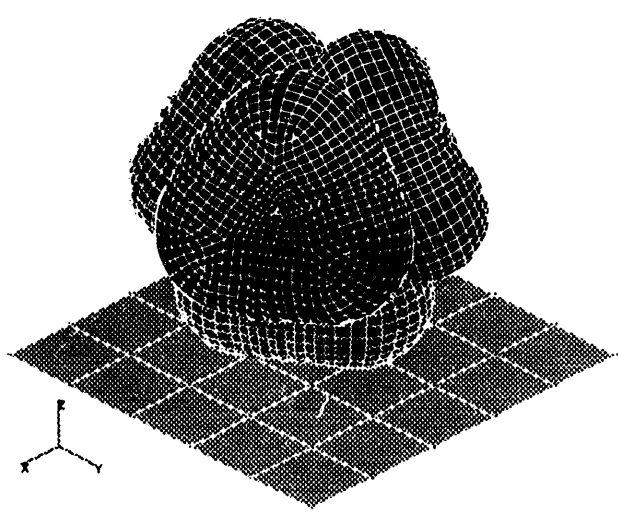

Figure 1. External View of Mars Lander Model

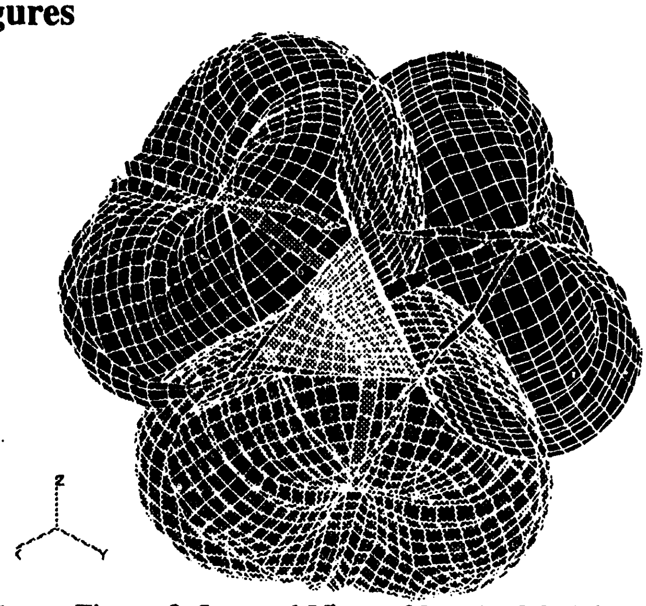

Figure 2. Internal View of Lander Model

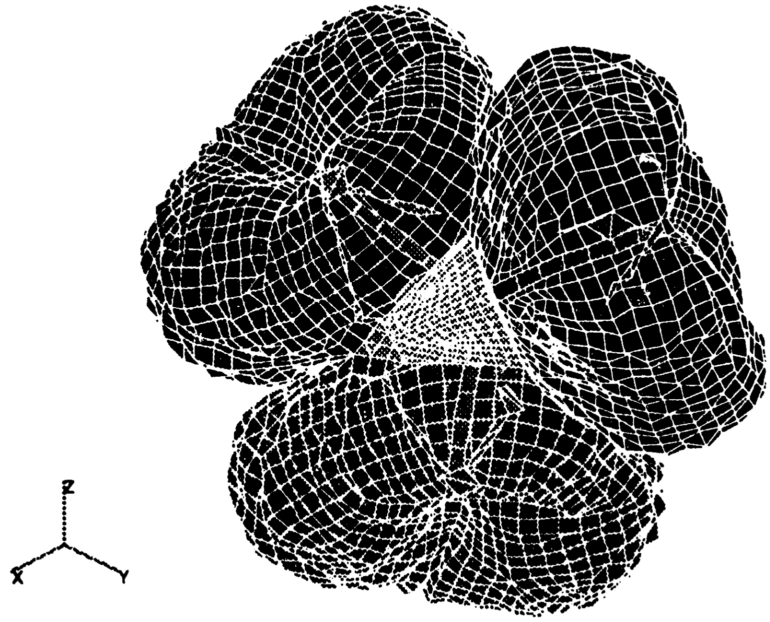

Figure 3. Internal View of Lander Model After Airbag Contact

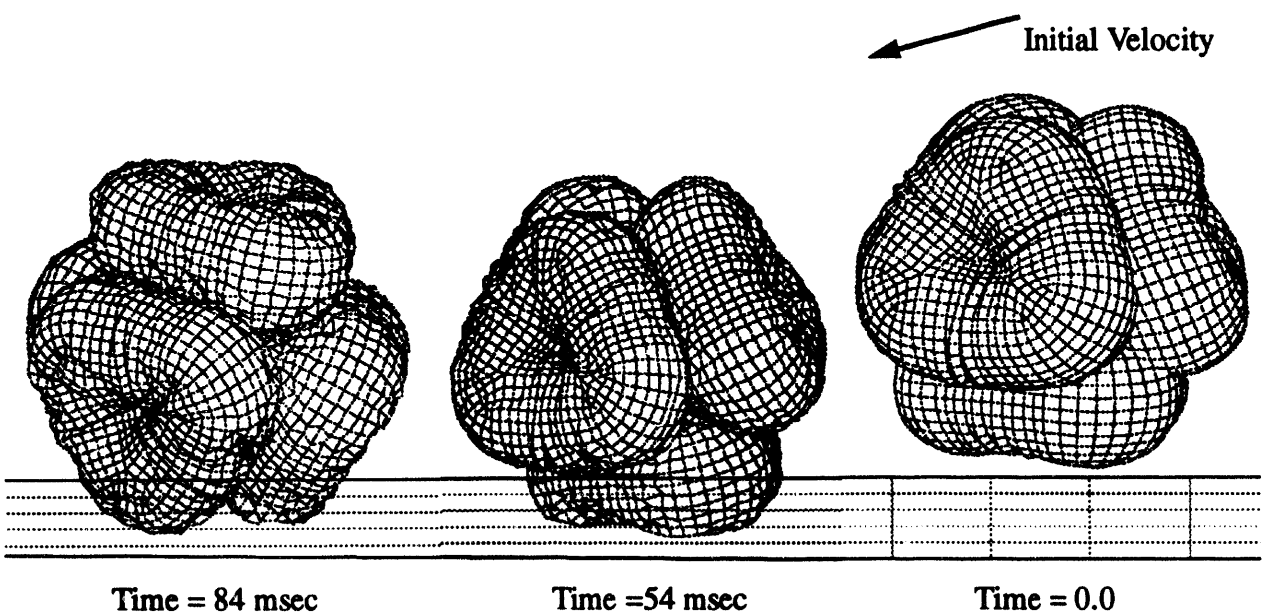

Figure 4. Deformed Shape at Various Times for an Oblique Landing

DISCLAIMER

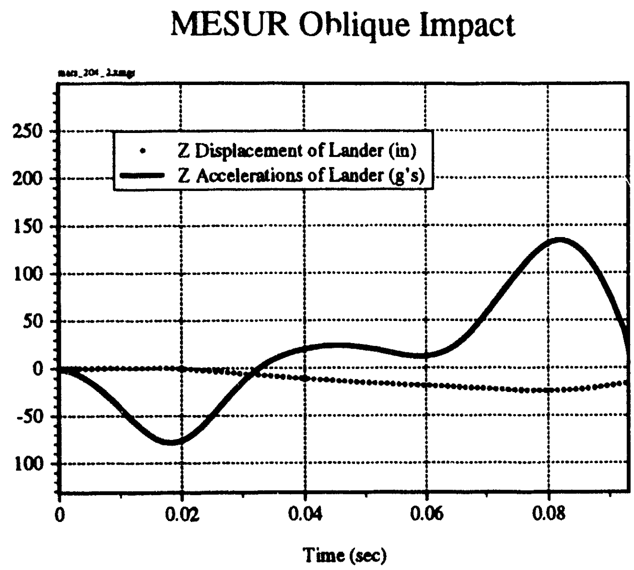

Figure 5. Acceleration vs. Time for Impact

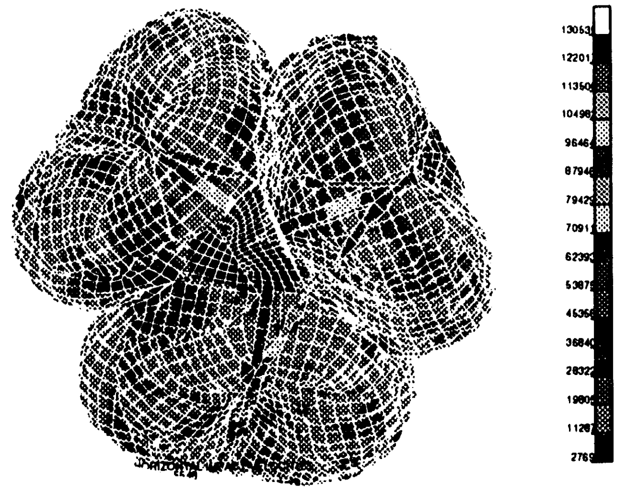

Figure 6. Maximum Principal Stress in Bags

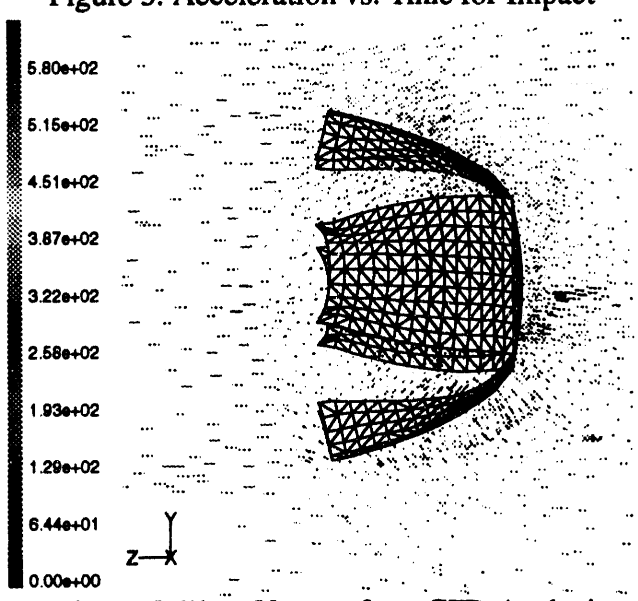

Figure 7. Flow Vectors from CFD Analysis

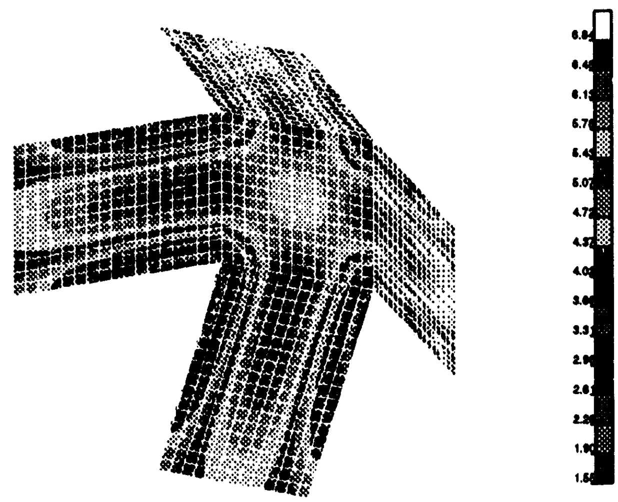

Figure 8. Pressure Distribution for Final Structural Analysis

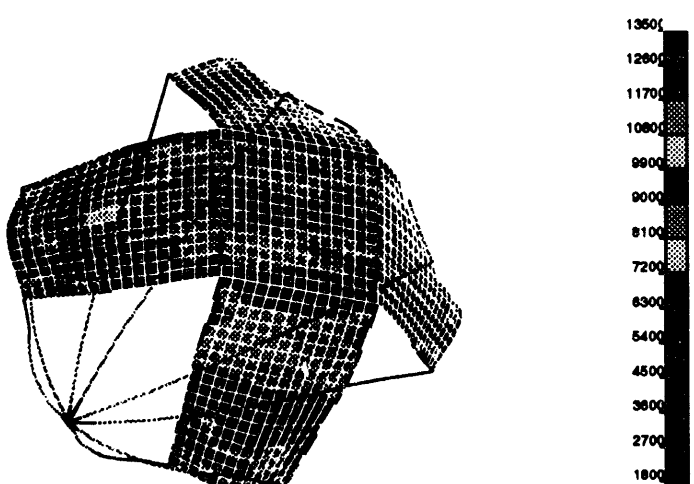

Figure 9. Final Deformed Shape and Warp Stress Distribution

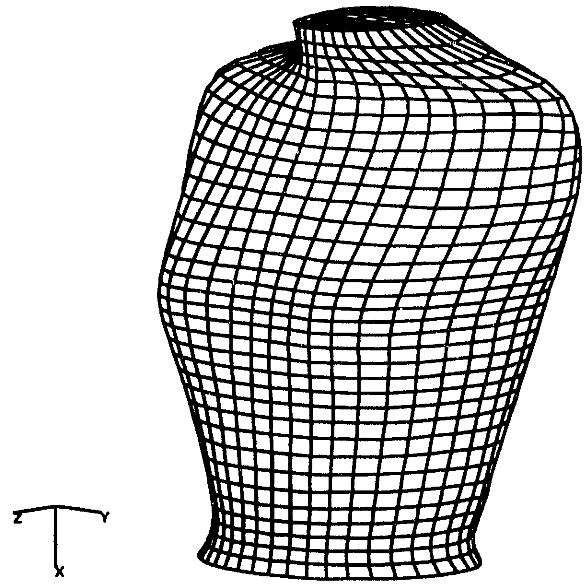

Figure 10. Garmnet Design Demo Model

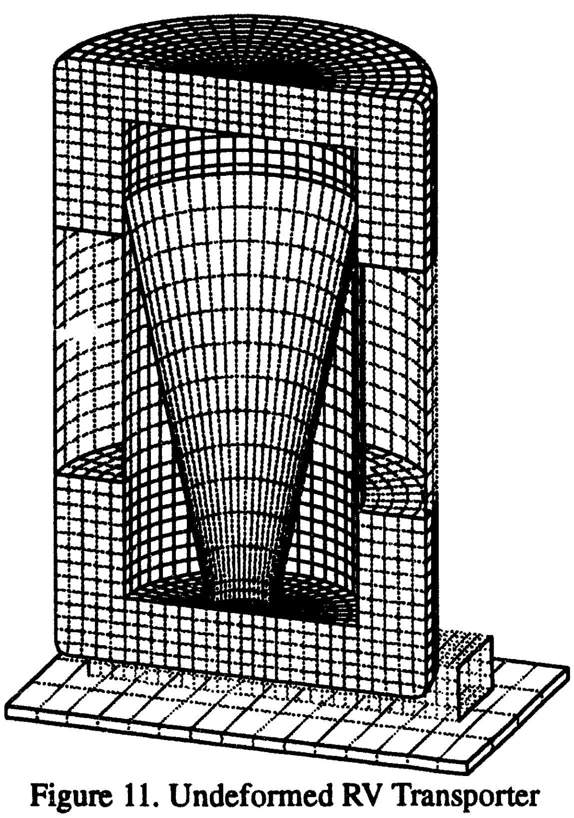

Figure 11. Undeformed RV Transporter

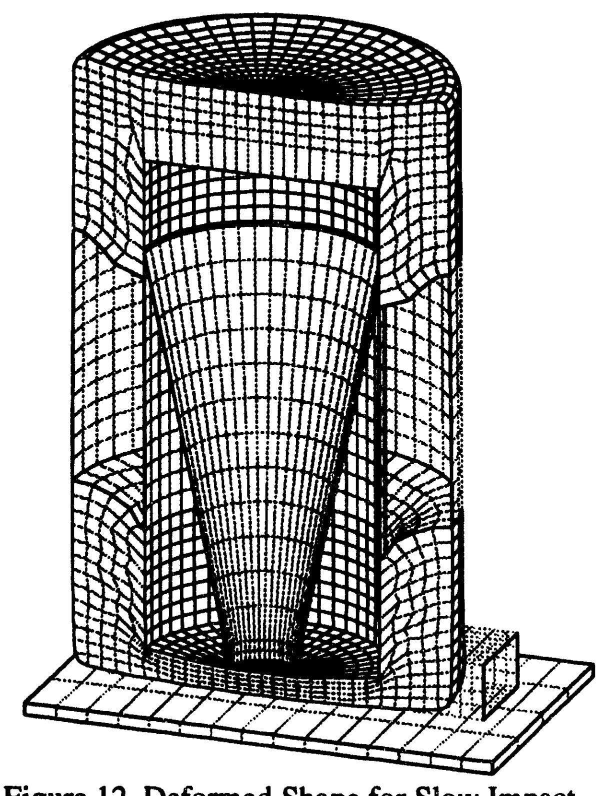

Figure 12. Deformed Shape for Slow Impact