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INVESTIGATION OF THE APPLICATION OF AIRBAG TECHNOLOGY TO PROVIDE A SOFTLANDING CAPABILITY FOR MILITARY HEAVY AIRDROP

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Irvin Aerospace Inc in partnership with the U.S. Army, Natick Soldier Center (Natick), have begun to explore the applicability of airbag impact attenuation for heavy airdrop delivery. The application of airbags (and other technologies) is being studied under Natick's Rapid Rigging De-rigging Airdrop System (RRDAS) program. The teaming of Irvin and Natick combines the experience of Natick airbag testing in the field of airdrop cargo impact attenuation, and Irvin's experience in airdrop development and impact attenuation for aircraft and spacecraft. One of Irvin's unique capabilities is the detailed simulation of airbag impact through explicit Finite Element Analysis (FEA) simulations.

Nomenclature

FEA - Finite Element Analysis
HMMWV - High Mobility Multi-Wheeled Vehicle
PMA - Pneumatic Muscle Actuator
RRDAS - Rapid Rigging De-rigging Airdrop System
TACOM - U.S. Army Tank Automotive Command

Introduction

The goal of the RRDAS program is to reduce the rigging and de-rigging time for typical Air Delivery loads up to 20,000 lbs. The concentration of this program is to replace the customary paper honeycomb impact attenuator with improved technology for soft landing. While this approach may not have an immediate financial imperative (paper versus modern technology), a review of a standard heavy drop rigging manual indicates many steps of honeycomb cutting, plywood cutting, gluing, and load assembly to create a conventional airdrop load.

Additionally, the RRDAS program is to improve the de-rigging time required following air delivery. Drop and drive versus drop, followed by a significant de-rigging time, will provide a tactical advantage.

Two soft landing technologies are under study. One is a Pneumatic Muscle Actuator (PMA), which provides soft landing through payload deceleration (by pulling up on the payload) just prior to landing. This development effort is led by Vertigo, Inc., with Irvin in a supporting role, and is the subject of many papers. (Reference 1)

The second technology under development depends on airbags between the Air Delivery Pallet (Type V), and the cargo. Natick, Warrick and Associates, and others have explored this work in the past years. Irvin currently has a contract to continue this development effort. Irvin's capabilities in previous airbag development programs, impact simulation (References 2-5), and fabric manufacture, make them qualified to continue this effort.

Simulation Description

This section details the simulations developed to assess the performance and design of a RRDAS airbag landing system. It is believed the detailed Finite Element Analysis simulations represent a virtual proving ground for the airbag concept.

Description Of Simulation Tool

The simulation tool used throughout the RRDAS program was the Explicit Finite Element Analysis tool LS-DYNA. The 950d3 release was used consistently throughout the program.

The temporal nature of the FEA approach, and unique features within LS-DYNA make it particularly effective for the analysis of airbag attenuated impacts and honeycomb or other impact problems.

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The unique features include the incorporation of airbag control volume/thermodynamics calculations within the FEA code. Other features include:

1) Incorporation of rigid body mechanics within the FEA code to reduce computation overhead.
2) Unique airbag controls such as acceleration and pressure-based airbag venting criteria
3) Airbag-to-airbag venting
4) Honeycomb and soil material models

Irvin's experience with the LS-DYNA tool spans multiple programs and multiple airbag configurations. Irvin is confident the results presented herein are representative of impacts achievable from a final airbag attenuation system. References (2-5) provide some of Irvin's experience related to airbag simulation.

Finite Element Model

The finite element model developed for this program consists of nearly 50 parts, and approximately 50,000 elements. Execution times vary between 4 and 6 hours for a 0.2 second solution, these runs being completed on a Pentium III processor with a clock speed of approximately 900 MHz.

A significant number of the elements mentioned above are dedicated to rigid bodies, which significantly reduces run time. However, the many parts involved dictate multiple part to part contact definitions. Approximately 40 percent of the simulation processing time is dedicated to the contact algorithms.

The addition of soil increases both the element count and simulation run time.

Body And Chassis

Figures 1 and 2 present the vehicle body and chassis meshes used for the Army's High Mobility Multi-Wheeled Vehicle (HMMWV) simulation. The body geometry is taken from a solid model provided by the U.S. Army, Test & Evaluation Agency (TEA). The solid model was imported (as a ParaSolid file) into the ANSYS preprocessor, and meshed. The mesh was then output from ANSYS and translated into NASTRAN Bulk data format. This was then imported into the LS-DYNA Preprocessor, FEMB.

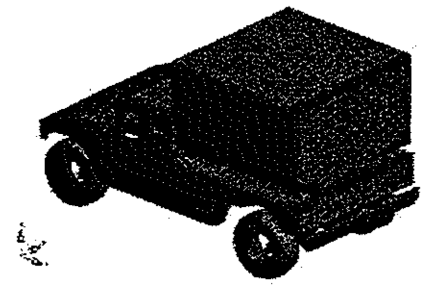

Figure 1 – View of HMMWV Body Mesh

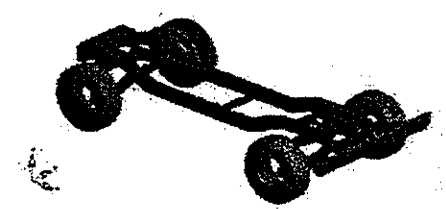

Figure 2 – View of HMMWV Suspension Mesh

The chassis mesh was received from AM General, the manufacturer of the HMMWV. Transmitted in NASTRAN bulk data format, this file was directly imported into FEMB, an LS-DYNA pre-processor packaged with the PC versions of LS-DYNA. Support for AM General's effort was provided by U.S. Army Tank Automotive Command (TACOM).

Both the body and chassis are modeled as rigid in current simulations since the vehicle is thought to be significantly stiff relative to the airbags. Rigid bodies are defined in the inputs in a manner which allows the explicit specification of the vehicle's mass properties, to include mass, center of mass, and mass moments of inertia.

Irvin has been informed by AM General/TACOM, that they believe there is significant deflection of the HHMWV during air delivery impact. Test data for honeycomb impacts seems to support this assumption. However, the vehicle deflections are still minor as compared to the airbag deformation, thus supporting our initial assumption of rigid modeling.

A more detailed model of the HMMWV during impact with airbags or honeycomb may be the subject of future RRDAS or other work.

Suspension And Tires

The tire model is a rather simple definition. The wheel is defined as rigid, and given a material density to approximately match that of the vehicle wheel. The tire is defined with shell elements which are rather stiff (having approximately the modulus of Kevlar®), and an inertia which provides the proper mass, as defined by TACOM, for the wheel/tire combination.

The tire tread, sidewall, and wheel, are then defined as an airbag control volume, allowing the tire model to react as an internally pressurized structure. The effective stiffness of the tire was checked with a dedicated simulation, which pushed the tire against a rigid wall, and reported the resulting force. Model comparisons to tire stiffness data provided by TACOM were very good.

The suspension model is somewhat sophisticated. The suspension control arm is modeled as a rigid body, with detailed geometry. A rotary joint attaches the top of the control arm to the vehicle chassis. The bottom of the control arm, and the wheel are merged, forming a rigid attachment. Spring elements represent the coil spring and shock absorber forces. Their characteristics were obtained from TACOM, and are different between front and rear. Figure 3 provides a view of the various components in the suspension model.

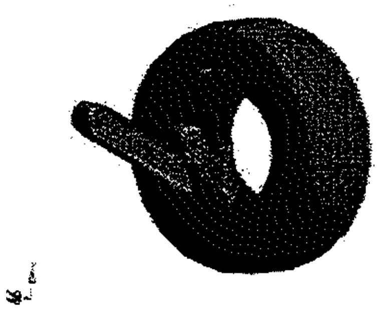

Figure 3 – HMMWV Suspension Model

Flexible Pallet

Early in the RRDAS program, our assumption of a rigid Type V pallet model was shown to be incorrect. Correlation to test data obtained by another program (Warrick) demonstrated the rigid Type V pallet model rebounded too dramatically following initial ground impact, at least for a rigid wall ground model.

Irvin then developed a flexible model of a Type V pallet. The resulting model, while rather coarse for detailed structural analysis, is acceptable for impact simulations, as it has little effect on the simulation time step.

Type V Pallet details were taken from engineering drawings provided by Natick, which include detailed representation of the side rails, fore and aft bumper guards, the upper and lower skins, and internal ribs of the panel extrusions. The material model is a piecewise linear model, allowing for plastic deformation.

Figure 4 presents a detailed view of the pallet mesh, while Figure 5 presents a view of the pallet during impact. The deformation of the aft end, we believe, is a proper representation of pallet response during landing.

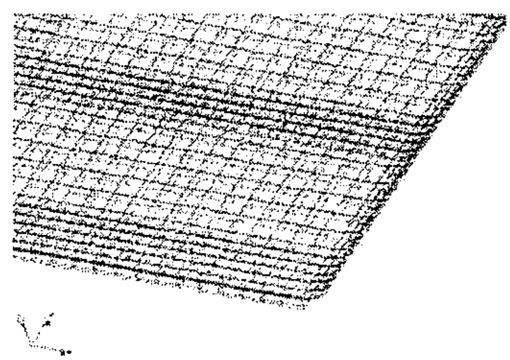

Figure 4 – Detailed Mesh View

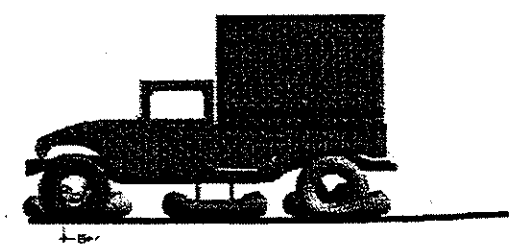

Figure 5 – Pallet Response During Landing Simulation

Airbags

Early in the RRDAS program, it became clear that shape control of the airbags would be critical. This is driven by the requirement to be no higher than the load as currently rigged on honeycomb. The square impact attenuation nature of honeycomb, required acceleration limit (approximately that of honeycomb), and the height restrictions, dictated a design that provided early and near square wave-type performance.

Additionally, the relative flexibility of the Type V pallet also dictated airbag shape control. An inflated and un-restrained airbag will tend to a spherical shape, and an airbag whose shape was restrained only by the vehicle and Type V pallet, would apply significant bending loads into the pallet. An overly warped pallet cannot be installed, or, more significantly, potentially cannot be extracted from an aircraft.

We therefore began with an airbag concept which incorporates integral metal plates into the top and bottom of the airbag. These plates are connected by internal straps, which prevent the expansion of the plates away from each other. The result is an airbag which has a relatively flat shape. This serves the dual purposes of providing early deceleration and minimal bending loads into the Type V pallet.

Figure 6 presents a view of the airbag FEA Mesh. The upper and lower plates have been modeled both as rigid bodies, and flexible bodies. In the flexible configuration, a mass optimization has not been complete. A nominal plate thickness of 0.25 inches for aluminum has been simulated and found acceptable.

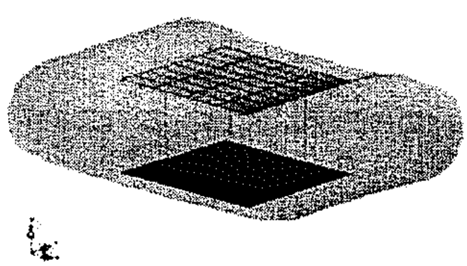

Figure 6 – Typical Airbag FEA Mesh

The LS-DYNA control volume approach for airbag computations (*airbag) is used to model the airbag thermodynamics. Nominal airbags have an initial pressure of approximately 12.0 psig. The vent area depends on airbag volume, as several airbag volumes have been simulated. In all cases, the *airbag_pop option is employed. This allows triggering vent opening based on a sensed acceleration of a rigid body. In general, an acceleration of 10 g's, at the HMMWV CG has been the criteria to initiate airbag venting.

Interface Structure

Several different approaches to the interface between airbags and vehicle structure were explored throughout the program. Our initial concept of a spread load application across the bottom of the vehicle was quickly dismissed. This approach initially appeared attractive given the large and flat areas, which are essentially the vehicle floor pans. However, initial investigation of the floor pan construction quickly revealed minimal load carrying capability exists here.

Several approaches requiring interface to the vehicle chassis were investigated. These included the use of honeycomb sheets, to fill some of the interface volume. This approach was quickly dropped based on input from the user community.

Many other options have been explored.

Finally, the use of metal structure for the interface was adopted as the baseline approach. This approach allows a modular design, and takes maximum advantage of the structural plates in the top of the airbag. Interface to the vehicle frame will be accomplished with metal cups, similar to the operation of a car jack. Telescoping tubes may provide a level of adjustment for a variety of vehicles. Figure 7 provides a view of the base lined interface structure.

Figure 7 – Interface Structure Geometry

Honeycomb Stacks

Honeycomb stacks were simulated to provide a reference between airbag simulations, and the current method, using paper honeycomb. Figure 8 presents the honeycomb stacks, which were created based on rigging manual FM-10-500-2.

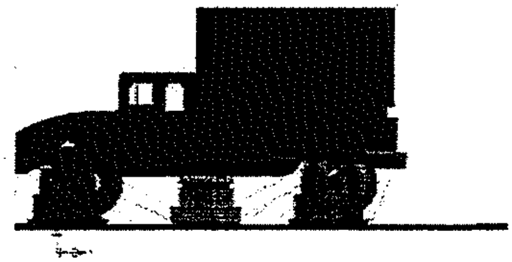

Figure 8 – View of Honeycomb Stacks

Honeycomb material characteristics were provided by Natick.

Two modifications were made to simplify the honeycomb model. The first was substituting rigid body characteristics for the wooden plates in the stack This provided a significant reduction in computational overhead.

The second modification was the slight narrowing of the upper plywood layer for the forward and aft stacks. As constructed, the suspension control arms can contact the upper plywood layer during the landing stroke. The assumption of rigid body properties for this layer creates a relatively stiff contact, and a resulting acceleration spike. In reality, we believe that the plywood would yield locally, eliminating this spike.

The approach was simply to substitute honeycomb elements for a few rigid wood elements. Figure 9 presents a view of the original and modified mesh for a forward stack.

Figure 9 – Modified Mesh for Rigid Plate Concern

Simulation Results

Herein we will discuss the performance data predicted by simulation for nominal landing, higher weight landings, broadside landings, potential for roll mitigation during broadside landing, reduced volume airbags, and comparison to honeycomb performance.

Finally, we close with an airbag fabric stress analysis, which provides the design basis for the construction of prototype airbags.

Nominal Impact

Figure 10 presents an acceleration time history for the vehicle CG during a nominal landing. The peak accelerations were lower than goals established at the program outset and, we will show later, are lower than the current performance, as demonstrated by honeycomb simulation and testing.

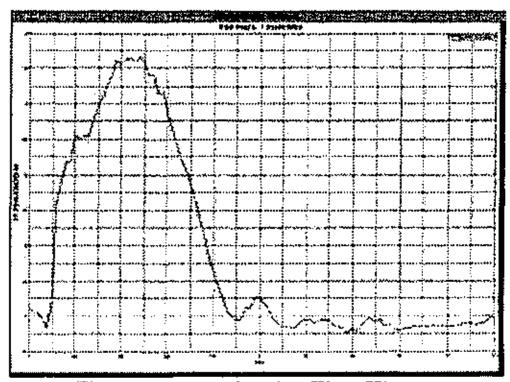

Figure 10 – Acceleration Time History

Vehicle weight for this simulation was 7,200lb, with approximately a 2000 lb Type V pallet. This represents the 10,000lb nominal configuration, which is a portion of the RRDAS Draft Operational Requirements Document (ORD).

Figure 11 presents airbag time history data for each airbag. An initial pressure of 12.0 psig is the starting pressure for each airbag. The airbag venting control is based on an acceleration threshold of 10.0 g's. At this sensed acceleration of the vehicle CG, the airbag vents are released.

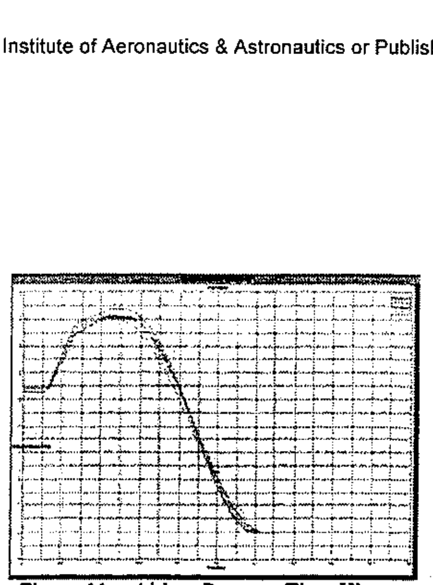
Figure 11 – Airbag Pressure Time History

One weakness of this configuration, as is seen in Figure 12, is that the forward airbag is slightly smaller than the others. This is primarily due to available space for the airbags. While this served as an initial starting point, we have since demonstrated that four (4) airbags of the smaller size, with slightly higher pressures, will equally well perform the airbag landing. This configuration is clearly superior from a logistics point of view, and will be adopted for the baseline configuration.

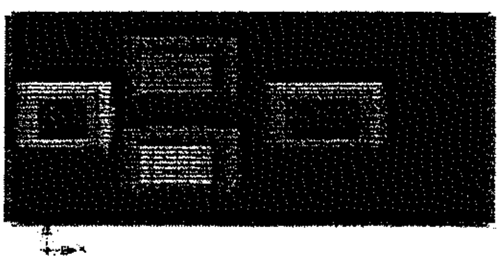
Figure 12 – Airbag Geometry

Scaling To Higher Weights

It has been demonstrated during the program that the landing of higher weights is possible by increasing initial airbag pressure. This is somewhat akin to using more honeycomb under a heavier vehicle. Additionally, for larger vehicles, the use of more airbags to land a larger vehicle is also quite possible.

Figure 13 presents the acceleration time history for the baseline landing case presented above, and for vehicles which are 50% and 100% heavier than the case above. All of these are successful landings. The only adjustment for the various weight cases is the pre-impact airbag pressure. Airbag vent area and control are identical for all simulations.

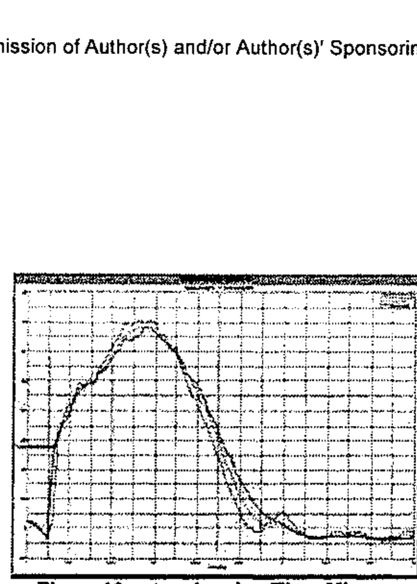
Figure 13 – Acceleration Time History
Landing Weight Variation

The operational adjustment of the initial pressure, we envision, would be accomplished through a simple knob adjustment on the airbag gas supply. This would control the pressure regulators, which set airbag pressure. As each load is weighed prior to aircraft installation, setting the airbag pressure at this point would be a relatively simple task, and checking of this setting would be a step in the Joint Airdrop Inspection (JAI).

Figure 14 presents airbag time histories for the three different weight landing cases.

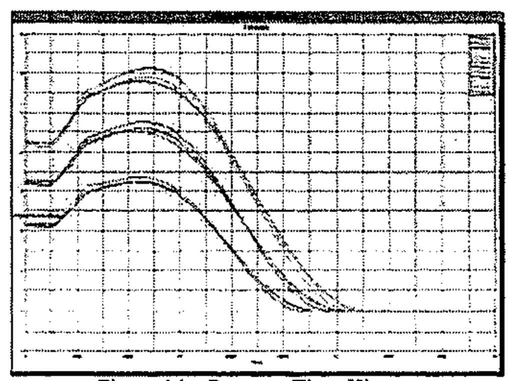
Figure 14 – Pressure Time History
Landing Weight Variation

Broadside Landing/Rollover Potential

One surprising conclusion from the simulation effort is the airbags are significantly less prone to rollover in high winds, than the current honeycomb kits. This is a result of the airbags tending to deform laterally during landing, while the honeycomb does not, leading to an early roll moment

Figures 15 and 16 provide snapshot views of the airbag and honeycomb landings, respectively. Similarly, Figure 17 provides a time history of the vehicle roll angle during landing. Landing conditions and vehicle mass properties are identical for both landing simulations.

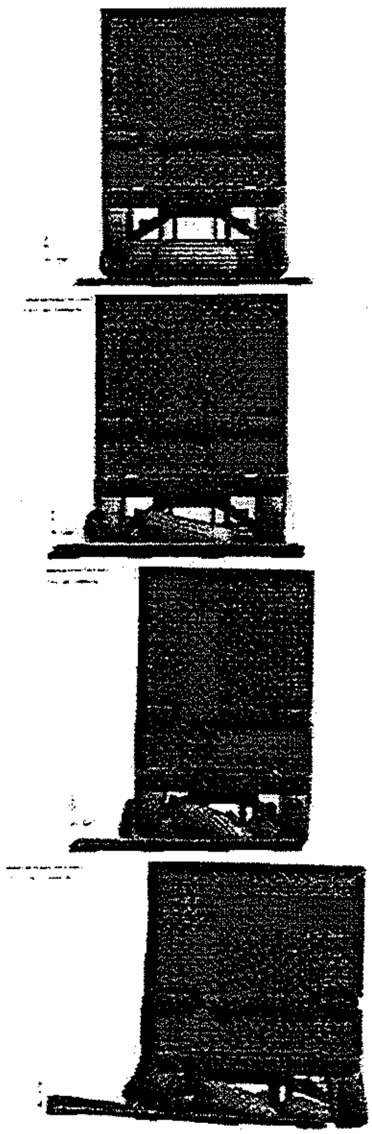

Figure 15 – Airbag Landing
17 Knots Broadside Landing

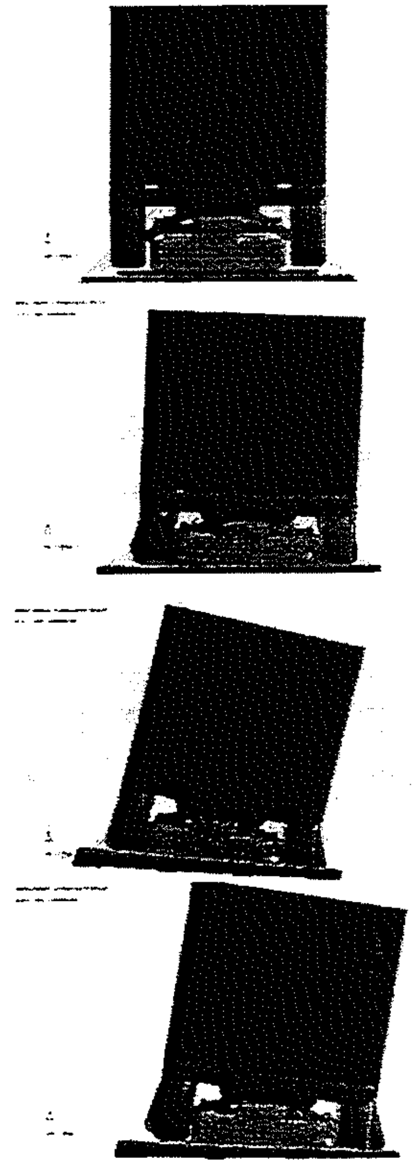

Figure 16 – Honeycomb Landing
17 Knots Broadside Landing

Based on the above data, we conclude the proposed airbag system will be significantly less likely to roll over due to high winds and broadside orientation. This may allow an increase in the allowable wind limits for air delivery of cargo. However, we recognize that the potential benefits of this may be reduced by wind limits for personnel airdrop which would not be increased.

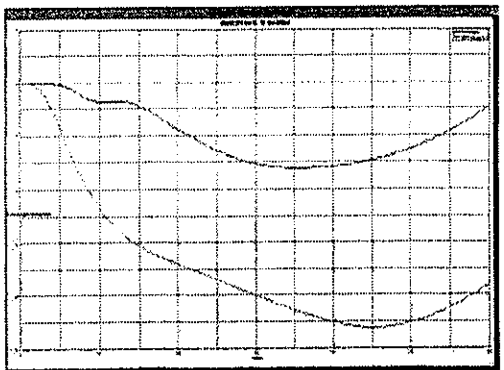
Figure 17 – HMMWV Roll Attitude Time History

Similarly, incorporating active control into the airbags might further increase heavy drop wind limits. In this approach airbag venting could be delayed to further reduce rolling moments during landing. This approach has been studied and demonstrated in simulation. However, given that the current airbag configuration appears to be better than honeycomb landings, we will not explore further in the interest of system simplicity.

Airbag Stress Analysis

Another output of the simulation tool applied for this analysis is the ability to produce stresses in the airbag throughout the landing stroke. These are used to assess the required strength for the airbag fabric. Figures 18 and 19 provide views of airbag stress for some of the higher stress landing cases, including the heavyweight case.

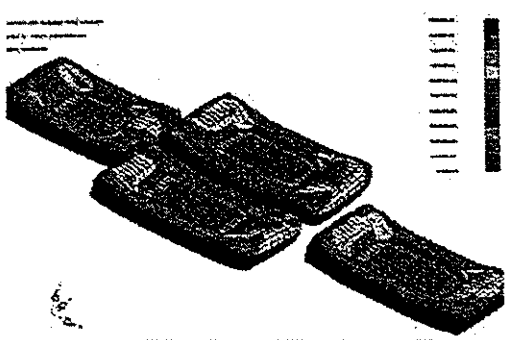
Figure 18 – Peak Airbag Stress – Nominal Landing

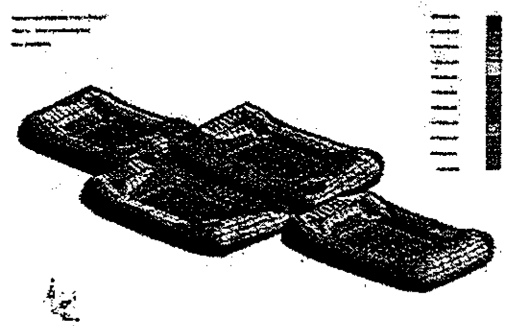
Figure 19 – Peak Airbag Stress
Heavy Weight Landing

Fabric stresses are converted to fabric running load by multiplying by the assigned fabric thickness in the simulation in this case 0.01 inches. Figure 18 indicates peak fabric running loads in the 250.0 lb/in range are expected. Applying a conservative design factor of 4.0, which would account for re-use factors, and other environmental conditions, we compute a required fabric strength of approximately 1000.0 lb/inch. This weight fabric is readily available, and is only slightly stronger than typical military fabrics, such as nylon duck material (600.0 lb/inch), which is typically used in parachute containers.

Additionally, our approach of minimal inflation pressure while in the aircraft will allow the demonstration of large safety factors while in the aircraft and around personnel. Only after the cargo exits the aircraft are the airbags inflated to their ground impact working pressure.

Comparison To Test Results

Warrick Two Bag Drop Tests

Warrick and Associates (WA), under separate contract, performed drop tests for Natick, with a slightly different airbag concept. The test data was provided to Irvin, as yet another opportunity to validate airbag impacts and our simulation tool.

The results of other airbag drop programs, and simulation comparison have been published by Irvin. References 2-5 provide some of these results.

Figure 20 provides a comparison of the Warrick drop test and the Irvin Finite Element model created to replicate the drop test results.

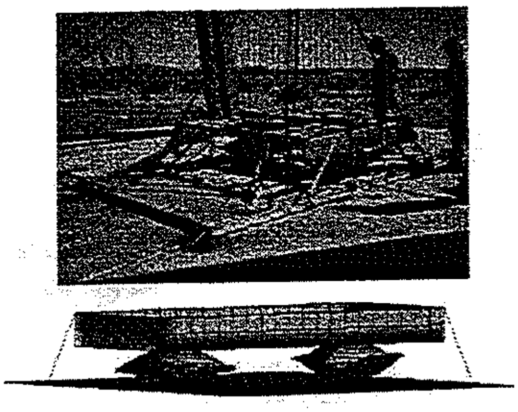

Figure 20 – Warrick Drop Test Model and Finite Element Model

Figures 21 and 22 provide comparisons of simulation and test results for sensed acceleration and airbag pressure.

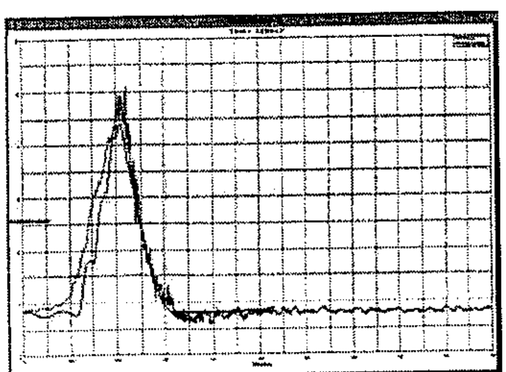

Figure 21 – Acceleration Time History Comparison

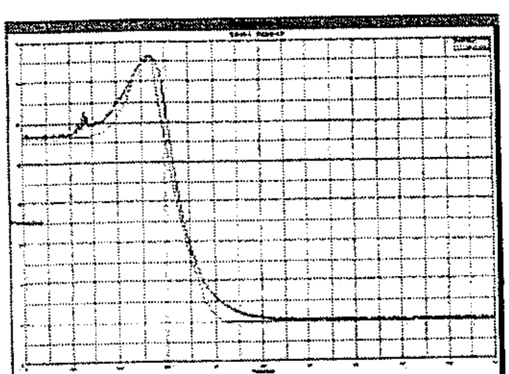

Figure 22 – Pressure Time History Comparison

Comparisons are good, and the level of correlation is consistent with data we have seen in other programs.

Conclusions

The Year One STO program has demonstrated the absolute feasibility of airbag landing for heavy airdrop, at least for the vehicle impact stage.

During this program we were able to leverage data from previous/parallel efforts, improving the concept design departure point, and credibility. From this we believe that the simulation results presented have excellent fidelity at least for conceptual development.

Year 2 investigations will serve to further refine the configuration, including the interface structure, single point rigging release, approaches for airbag inflation and load stabilization, as well as testing to validate the baseline airbag configuration.

We believe that the only major limitation to fielding an airbag-based soft landing system for military heavy cargo remains in the system level details, such as the airbag pressurization system, airbag re-use qualification, operational re-use certification, and aircraft certification.

These issues, and an tactical demonstration will be a key focus during the Year 2 program.

References

1. Brown, G. Haggard, R. Benney, R., "Parachute Retraction, Soft-landing Systems using Pneumatic Muscle Actuators" AIAA-2000-4308
2. McKinney and Taylor, "Use of LS-Dyna to Simulate the Airbag Landing Impact Attenuation of the Kistler K-1 RLV", 5th International LS-DYNA Users Conference 1998
3. Taylor, A. P., "Design Optimization of the Beagle II Mars Lander Airbags Through Explicit Finite Element Analysis", AIAA paper 99-1743
4. Taylor, A.P., "Explicit Finite Element Analysis of Fabric Systems, Real World Applications" 16th Aerodynamic Decelerator Systems Technology Conference, AIAA 2001-2002
5. Taylor, A.P., "Explicit Finite Element Analysis of Fabric Systems, A Comparison to Test Data" 16th Aerodynamic Decelerator Systems Technology Conference, AIAA 2001-2003