THE CASE FOR EXPLICIT FINITE ELEMENT ANALYSIS OF FABRIC SYSTEMS,

A PRESENTATION OF REAL WORLD APPLICATIONS AND RESULTS

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This paper presents the application of Finite Element Analysis (FEA) to real world problems typically encountered in the Aerodynamic Decelerator Systems field, and to fabric engineering in general. All simulation results are presented from the commercially available Explicit FEA package LS-DYNA, as this has been our most successful application. Our experience with the application of Implicit FEA, is that commercially available codes cannot handle the large deflections associated with fabric systems. The presentation of test to simulation comparisons, now available from several projects, is also presented herein. These provide the reader with a feel for the level of precision/validation possible with today's simulation tools. Finally, we close with a discussion of where Irvin, and eventually our industry, will apply computational techniques in the coming years.

Nomenclature

FEA - Finite Element Analysis
HOPEX - H-II Orbiting Plane Experimental
HSFD - High Speed Flight Demonstrator
PMA - Pneumatic Muscle Actuator
RRDAS - Rapid Rigging De-rigging Airdrop System

Introduction

The application of Explicit FEA, to fabric systems, began at Irvin in the mid-1990's, with the analysis of large airbag systems for the Kistler Aerospace Program (Ref. 2-4). Implicit FEA had been introduced earlier for metal parts (ANSYS), but proved virtually useless for airbag analysis, and fabric structures in general due to the large deformations involved.

Since that introduction, and subsequent assimilation of the Explicit simulation capability, we have applied this tool to multiple systems combining rigid, flexible, and fabric parts, dynamic and quasi-static problems, and continue to extend these applications.

Some of our current application areas include:

1) Airbags for aircraft/spacecraft recovery
   - Kistler Aerospace
   - NASDA/FHI HOPE-X HSFD
   - ESA Beagle II
   - US Army Natick, RRDAS Program
   - NAL Jet SSTS Program

2) Harness Deployment Simulations
   - Kistler
   - Coleman Aerospace
   - FHI HSFD

3) Fabric Retention Structures
   - Large Nets for Launch Stand Umbilical Impact
   - Retention Blankets for Missile Carriage Release

4) Other Unique Applications
   - A generic Pneumatic Muscle Actuator
   - Heavy Webbing Cutting Applications

5) Beam Buckling Problems
   - Irvin DLF – 3 Internal Beam
   - Rapidly Installed Breakwater System (RIBS)

6) Parachute Stress Analysis
   - A substitute for Sandia's CALA/CANO

7) Fluid Structure Interaction
   - Water entry problems
   - Certain parachute problems

Herein, we will review a few of these application areas, providing examples of the simulations results available, and how these data provided value by influencing configuration development, as this the ultimate goal of FEA and Computer Aided Engineering in general.

A comparison of these simulations to test data is also presented herein, providing a reference for the level of correlation possible in these very dynamic events. A discussion of potential simulation improvements is included. Finally, we close with a discussion of developing applications, both in terms of Irvin expertise, and in emerging capabilities in the LS-DYNA tool and other simulation capabilities. The LS-DYNA code incorporates a significant fluids solver capability, and unique user friendly approaches to coupling of the Fluid and Structural Elements. This capability should lead to an eventual parachute simulation capability.

Airbag Applications

As indicated above, airbag simulations have been completed for several programs. Of these, the Kistler program is thoroughly covered in References 2-4. New test results for two more applications have been developed with one presented herein.

We will concentrate on the NAL/NASDA/FHI High Speed Flight Demonstrator (HSFD) program in examining the application and its effect on configuration development and presenting test comparisons.

A Discussion of Airbag Simulations In LS-DYNA

One of the unique features of the LS-DYNA simulation tool is the inclusion of control volume and thermodynamic calculations for pressure vessels. These were originally developed for the simulation of automotive airbags. In recent years Irvin and others (Mars Pathfinder Program) have requested and LSTC has provided significant additional capability to allow the easy simulation – including control algorithms – of airbags more typical of the Aerodynamic Decelerator Systems community. Our close relationship with LSTC, and their rapid addition of features to the simulation, has been pivotal in making this work possible.

The airbag simulation within LS-DYNA allows the specification of a 'control volume' and the thermodynamic properties of the gas inside the control volume. Typically, this would be (in an airbag application) the outer structure of the airbag. Once the airbag definition is completed, the simulation automatically updates the thermodynamics calculations for airbag pressure, airbag in/out mass flow, etc., and applies the resulting gas pressure to the airbag structure. Airbag loading into a vehicle is accomplished through contact algorithms.

Multiple unique features allow control of the airbag initial pressure, inflation, and venting, by various means. These include venting as a function of airbag pressure, time, or constant orifice area venting. Additionally, algorithms for inflation control and vent control provide for time, pressure and body acceleration controlled events. Airbag to airbag venting is another option. As is the ability to model blockage of the vent as it comes in contact with another body.

High Speed Flight Demonstrator

Explicit FEA had a profound effect on configuration development for the HSFD airbag configuration. Figure 1 below presents several configurations, which were explored, by computer only. Once the initial simulation was built, models of these geometric modifications could typically be built in less than 8.0 engineering hours. Depending on the level of exploration required, a configuration could be explored and eliminated/morphed virtually over-night. Run times for these simulations were 2-10 hours on PC workstations, applicable computer details are provided in Appendix 1. The HSFD program is a scaled free flight model of a future space craft being developed by the Japanese Space Agency NASDA.

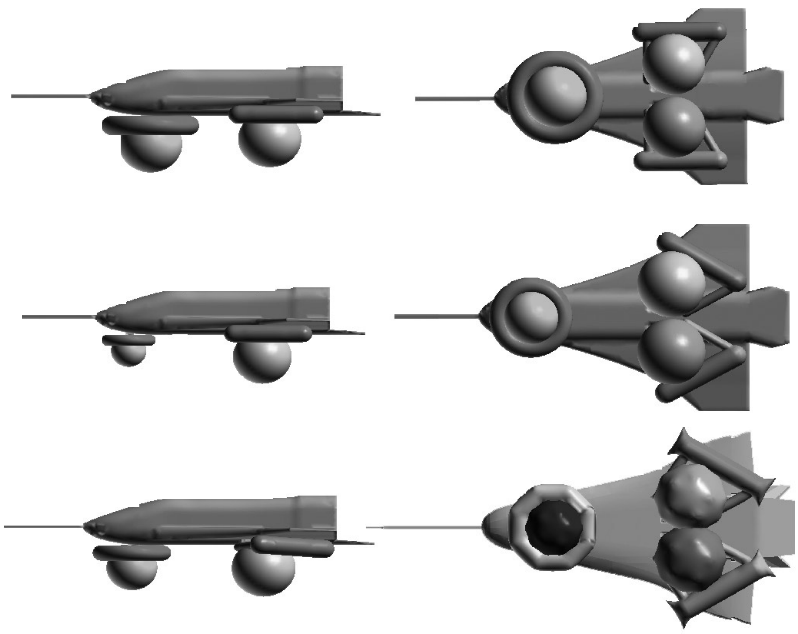

Figure 1 – Virtual Airbag Configurations

Figure 2 presents the final airbag configuration. Changes in the configuration included a stiffening of the anti-bottoming airbag arms, through diameter increase, optimization of landing control to minimize roll attitude departure/wing tip strike, and modeling of the airbag vents to account for ground obscuration of the vents.

Addition of the orifice blockage, already available in the LS-DYNA simulation program, provided a significant tool for assessment of proper vent locations within the airbag.

As the vehicle wind orientation and attitude was arbitrary relative to the wind, this proved a challenging problem with regard to airbag vent blockage. However, a large database of landing simulations existed, where the orifice was present from the airbag control volume point of view, but not physically modeled in the finite element mesh. This allowed the investigation of candidate locations, including the potential for vent obscuration either through vehicle or ground contact. Figure 2 presents the final vent configuration.

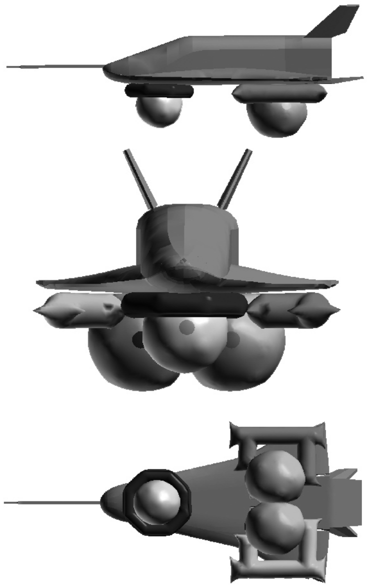

Figure 2 – Final Airbag Configurations

NAL/NASDA HSFD Airbag Testing

One of the first steps to testing airbags – in the Irvin system – is the calibration of airbag orifices before impact test. This is accomplished by inflating and deflating the airbags from several (3 or more) initial pressures. Pressure decay versus time is measured and compared to a simulation of the same event.

Several pressures are used to eliminate uncertainties due to airbag final volume, and the output of the analysis is a rather precise value for the orifice discharge coefficient. In general, we expect this value to be close to the classical sharp edge orifice value of 0.70. However, higher values have been documented due to fabric elongation effect, as have lower values due to complex vent flow fields.

Figure 3 and 4 present a comparison of test and simulation data for two such tests – in the third the data was lost. The comparison appears quite accurate, and in this case agrees with the theoretical value of 0.70 for Discharge Coefficient (Cd).

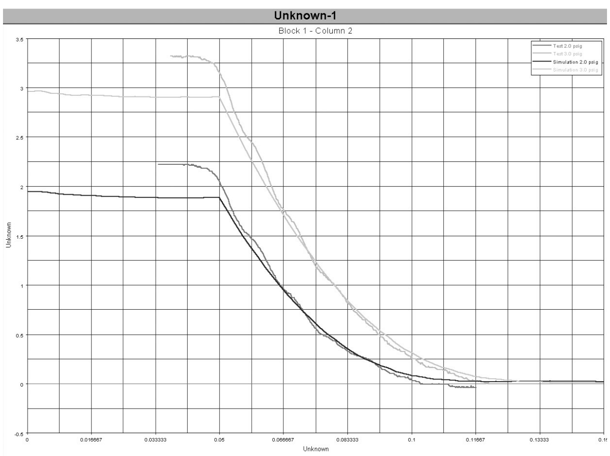

Figure 3 – Aft Airbag Orifice Calibration

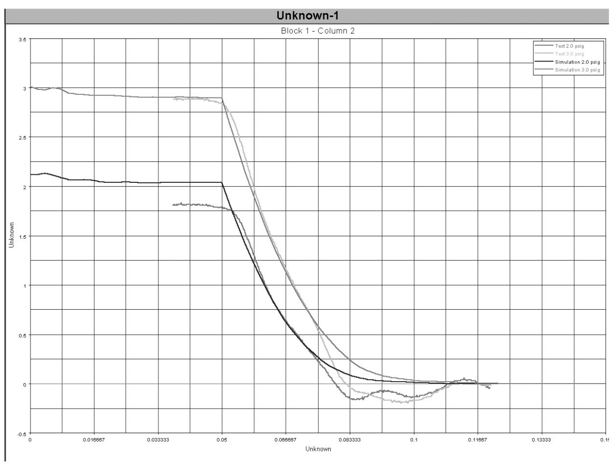

Figure 4 – Forward Airbag Orifice Calibration

One of the unique aspects of the HSFD requirement is the persistent blocking of airbag vents at the edges of the landing envelope. This is primarily due to the unique geometry requirements, and the all aspect landing orientation of the vehicle. The vehicle has a relatively flat bottom surface, and airbags are located well inboard due to available compartment locations. This creates of scenario of virtually two flat plates, sandwiching airbags between vehicle and ground plane.

This required the simulation of airbag vent blockage, which is currently available within the LS-DYNA simulation package. Herein we present test to simulation correlation, but more importantly, we present the effect of airbag vent blockage, and the improvements available when this important effect is included.

Additionally, the HSFD airbags are constructed on Nylon fabric, as compared to Kevlar in the Kistler example. We therefore also provide evidence of the simulation tools ability to handle varying material modulus, and predict accurate results.

Figure 5 presents a view of the drop test model installed in the test track, prior to drop test. Figures 6 and 7 present views of the test impact – note the airbag vent blockage, as illustrated by the soil/dust disturbance. In Figure 6 we present a similar view of vent blockage from an LS-DYNA simulation.

Figure 5 – Airbag Drop Test Facility
Airbag Vent Blocking Against the Ground

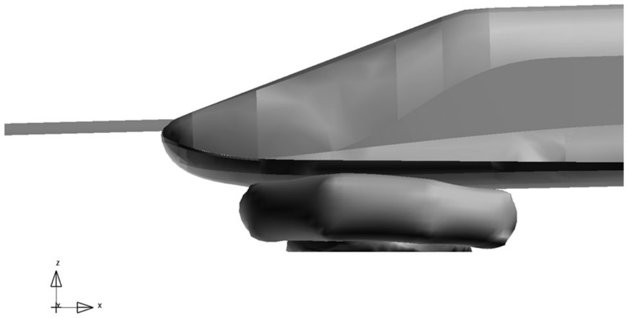

Figure 6 - Simulation Result

Figure 7 - Drop Test Impact
Airbag Vent Blocking Against Ground

Figures 8 through 12 present test comparisons for the pictured impact, where the airbag vents were blocked by the ground. Vent blockage was not originally considered, but quickly added when these results were observed. As stated earlier, in many configurations this is a minor obstacle.

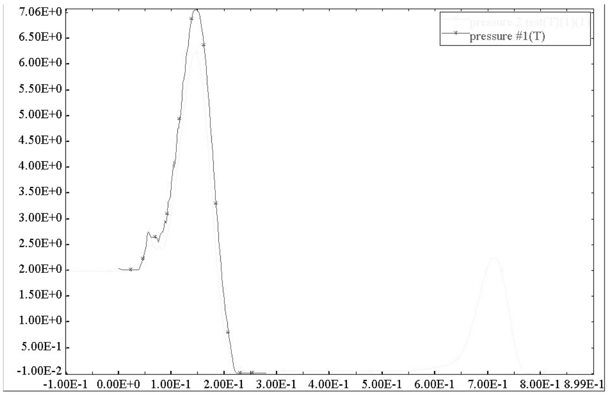

Figure 8

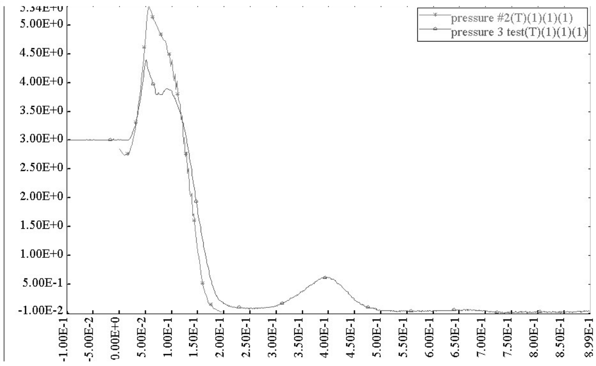

Figure 9

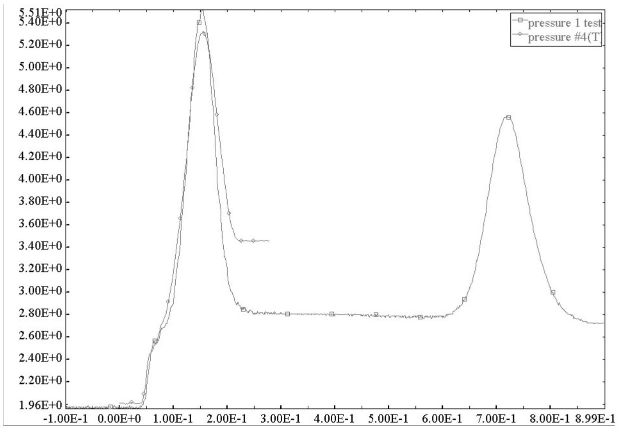

Figure 10

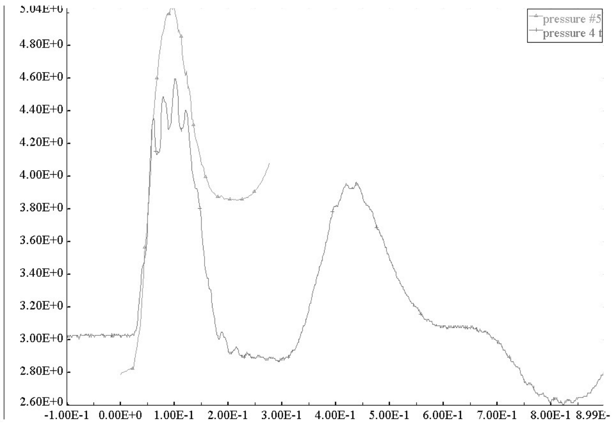

Figure 11

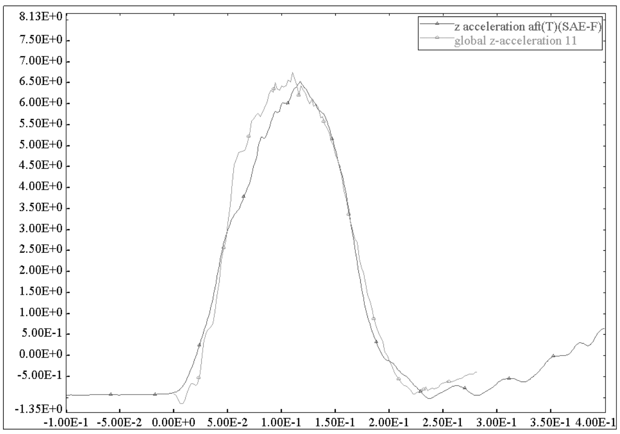

Figure 12

The results presented are rather preliminary in terms of the program scope, as airbag system design changes are being finalized at the time of writing. However, these rather preliminary results are rather compelling.

Figure 8 presents a pressure time history for the forward venting airbag. Comparison to test is very good, and this bag experienced heavy vent blockage.

Figure 9 presents pressure time history for the aft venting airbags. While we believe that this comparison is acceptable, and good for a first analysis, we also believe that further investigation will serve to close the difference. Again, the reader is reminded, that there are no arbitrary factors that we adjust to improve correlation, rather, we search for physical differences between the drop test model and the FEA analysis.

Figures 10 and 11 present the pressure time history for the forward and aft anti-bottoming airbags, respectively. In general here, the comparisons are acceptable. As the airbags include gas venting (one-way) between the main stroking bags, and the permanently inflated anti-bottoming bags, this is the explanation for the disagreement.

The simulation airbag definition allows the specification of a gas flow path, however, the pressure time history results clearly indicate that the full gas path is not present, probably due to airbag deformation. The bag to bag flow path is a mathematical entity in the simulation (at this point), not a geometrical entity.

We believe that this explains both the post peak level (lack of correlation) in Figure 10, and the peak level and post peak level (lack of correlation) in Figure 11. These could easily be adjusted in the simulation, or modeled in detail through an FSI approach, if required. However, these flow paths were deleted from the design shortly after these results were completed.

Figure 12 presents a comparison of test and simulation for the vehicle CG acceleration during impact. Similarly, Figure 13 compares the acceleration at a point in the nose of the vehicle. This location included a vertical acceleration measurement during test. Close comparisons in both indicate that we have captured both the overall vehicle acceleration, and the resulting pitch motion – important for predicting the dynamic ground strike potential envelope of the vehicle during landing.

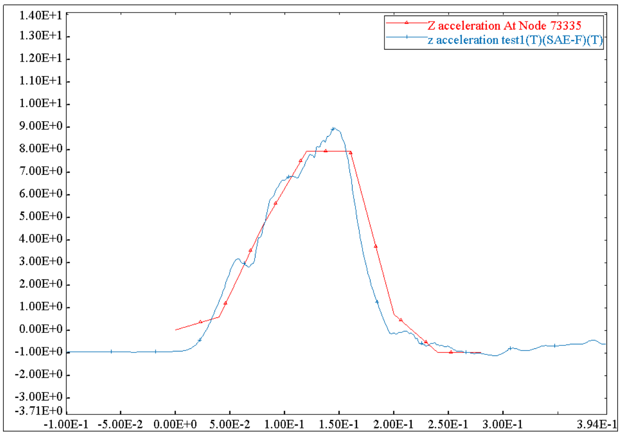

Figure 19

A Generic PMA

The application of Pneumatic Muscle Actuators (PMAs) is well documented by Vertigo Inc, and others (Reference #8)

Herein we present a simple LS-DYNA model of a PMA, consisting of beam elements, which represent the fabric structure, and shell elements, which represent the PMA liner and the LS-DYNA control volume.

The top of the PMA is fixed, and the bottom is assigned a mass. Figure 14 presents a detailed view of the beam and shell elements which make up the FEA mesh.

In Figure 15 the PMA is inflated with an arbitrary gas flow rate. The resulting system contraction is demonstrated.

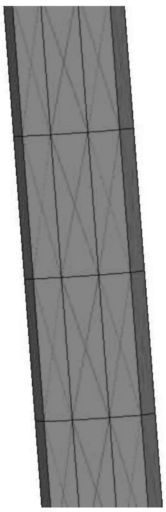

Figure 14

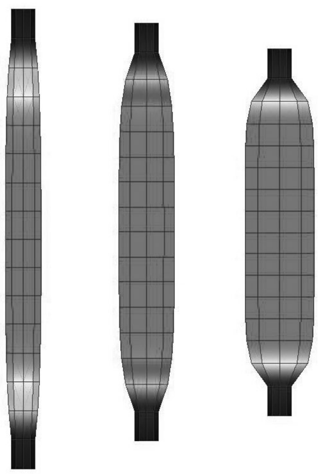

Figure 15

Umbilical Nets

Irvin was involved in the development of impact nets to decelerate umbilicals for a modern satellite launch system. Performance criteria for the nets included the maximum force applied to the umbilical, maximum deflection of the net, and a required safety factor and re-use capability for the nets. These requirements for high performance, combined with the rather expensive and fragile nature of the impact item (umbilical), lead to the requirement to perform impact simulations (on the computer) to optimize the design.

Additionally, the high mass, and high velocity of these items dictated a level of detailed analysis prior to testing. The umbilicals (three different configurations) have weights in the 100 to 600 lb range, and as they are T0 umbilicals, are retracted at velocities up to 30.0 fps in order to clear the ascending launch vehicle. Three separate umbilical configurations were simulated, and multiple net configurations were constructed for each umbilical (in the virtual world), before arriving at a final design. Figure 16 presents a collage of impact frames for two of the umbilical configurations.

Key features of each of these models include:

1) Modeling frame and umbilical as rigid bodies with appropriate mass properties

2) Rotary joints at net frame top to model hinge

3) Non-linear discrete element models dash pot damper near frame bottom

4) Net modeled as fabric elements – including orthotropic behavior

5) Umbilical impact simulated at several locations on the net

Simulation outputs included:

1) Net Stress

2) Net Deflection

3) Net Force into Frame

4) Effect of Slack and Reuse in Net

5) Effect of Impact Variation

a. High Impact

b. Mid Impact

c. Low Impact

d. Impact Body CG and Rotation

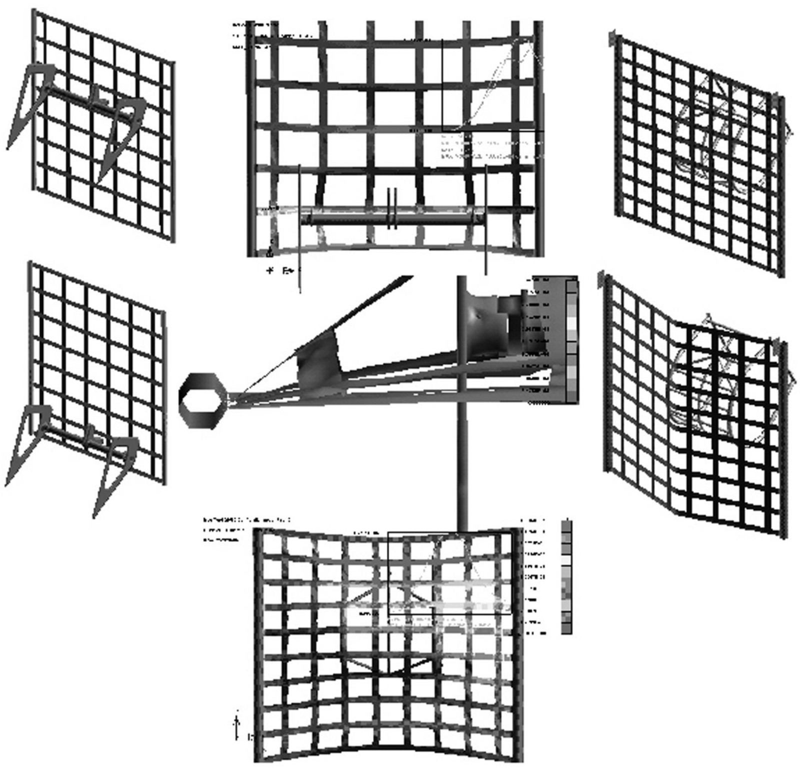

Figure 16

Umbilical Nets – Test Correlation

Test data presented below are for the net qualification program. The test configuration consisted of a ballasted steel pipe, which was dropped vertically onto a horizontally mounted net. Figure 17 presents a view of the finite element model that simulated the test. Test conditions were an impact mass of 650.0 lb with an impact velocity of 30.0 fps.

Impacts into new and used nets, including slack in new nets (manufacturing tolerance) and slack due to mechanical set, as with used nets. Additionally, a wet net was tested, which would represent an adjustment for net slack, density and modulus. Herein, we present only the dry drop test data.

Wet net results were less conclusive, however we have concluded that our representation of the effects of water absorption on Nylon fabric was not fully correct in our initial analysis.

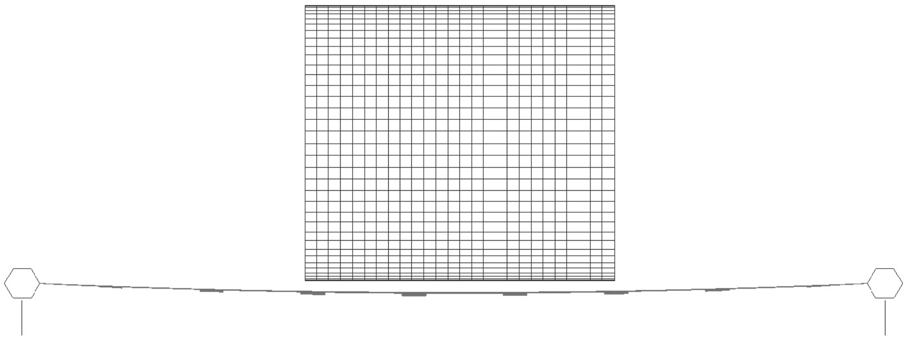

Figure 17 – FEA Model

Figure 17 presents a view of the FEM just prior to impact. The net qualification model, a steel ballasted pipe, is shown just prior to net impact. The effect of gravity can be seen in the net mesh.

Figure 18 presents an acceleration time history for the model impact against a new net. The acceleration growth and peak acceleration are remarkable as compared to the test data. We believe that the post peak difference is almost completely due to the linear material model (simulation) versus the actual hysteretic behavior of fabrics, particularly webbing weaves.

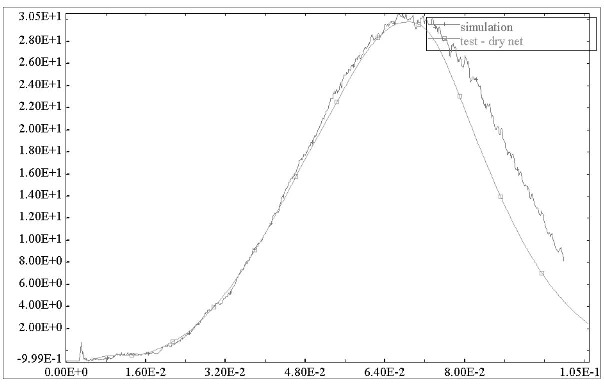

Figure 18 - Deflection Comparison
Dry Net, First Impact, Adjacent Element
(Deflection (in) vs time(s))

Figures 19 and 20 present comparisons of net deflection between test and simulation. While these results are interesting, they are certainly not as compelling as the acceleration results. However, as the measurement device for deflection is a string-pot device, we consider the test measurement less certain than the acceleration.

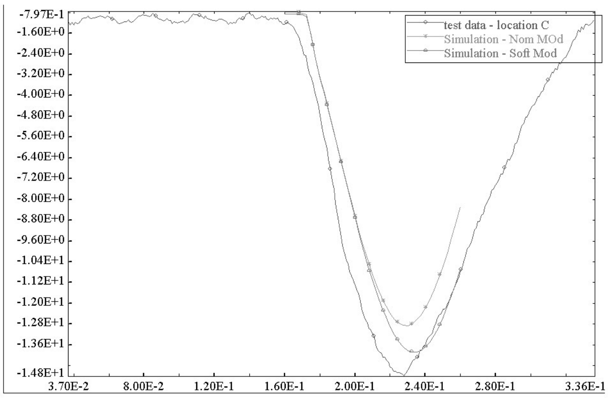

Figure 19 - Deflection Comparison
Dry Net, First Impact, Impacted Element
(Deflection (in) vs time(s))

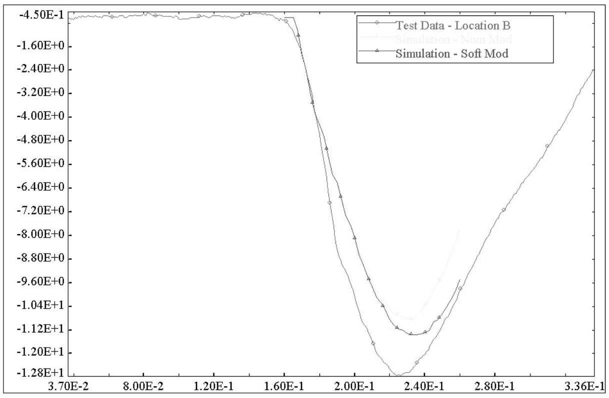

Figure 20 - Deflection Comparison
Dry Net, First Impact, Impacted Element
(Deflection (in) vs time(s))

Conclusion

Finally, we present a brief discussion of the future of such simulations, as they might affect our industry. First, simulation improvements are almost daily. Irvin experiences excellent support from the software vendor (LSTC), with unique code improvements, to our specification happening often. Actually, we are typically, 1-2 releases ahead of the production release due to unique features, and often receive these updates in days (or less).

Secondly, computer resources continue to soar, making the level of problem per hour of computation proceed at the same rate. Additionally, improved turn around improves the model development time, as shorter runs shorten the mistake/correction cycle.

One coming technology will be the application of Massive Parallel Processing (MPP) to this simulation tool. LSTC is investing heavily in this area. Imagine all your high-end CAD stations working together on analysis programs overnight, instead of sitting idle. Standard network connections (10BaseT or 100BaseT are the planned interface between various computers). The light bill is easily balanced by the improved resource allocation.

Finally, the significant fluid capability currently available in this tool provides the ability to explore true Fluid Structure Interaction (FSI) problems. The current capability represents a Navier-Stokes solution with a moving mesh. The current fluid-structure coupling capabilities are impressive, allowing rather simple fluid to structure coupling, and are rapidly expanding.

Modeling of fabric porosity is currently being reviewed and the ability to model multiple materials within the same mesh (air and water) is currently available, Figure 21 presents a water entry problem, which utilizes these capabilities.

With regard to parachutes, the obvious early applications are not related to parachute inflation simulation. That will come with further computing advances, that is, these problems will be possible in a few years, at high speed computing centers. Industry application will require multiple years of advancement in both hardware and software, but it will come.

Rather, we believe that parachute design can benefit immediately from computer assistance to age-old problems such as:

1) Porosity optimization between drag and stability
   - a. Single Canopy
   - b. Clusters

2) Geometry optimization
   - a. Line Length
   - b. Pull down vent length
   - c. Cluster riser length

3) Glide/drive optimization
   - a. Venting/drive panel
   - b. Riser slip condition

Figure 22 presents the inflated profile of a cross parachute (1/4 symmetry), as completed through an early attempt at FSI simulation of parachutes with LS-DYNA. Figure 23 adds a view of the fluid flow field total velocity around the inflated parachute.

We believe that initial results, perhaps as significant as the airbag configuration data presented above, will be the subject of our paper at the next ADS conference, certainly, within the four (4) years between now and the 2005 conference.

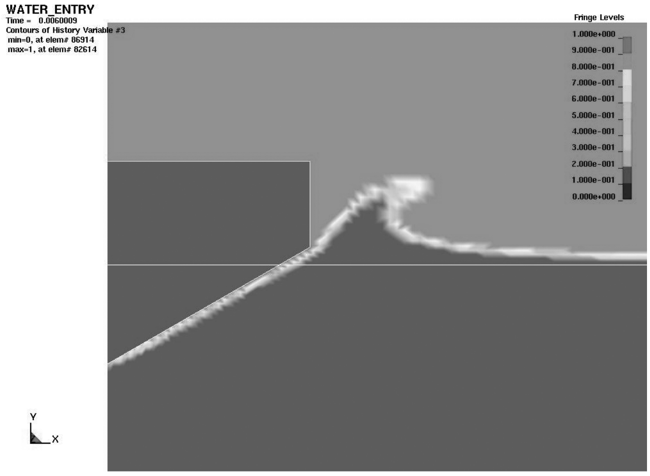

Figure 21 – Water Entry Problem

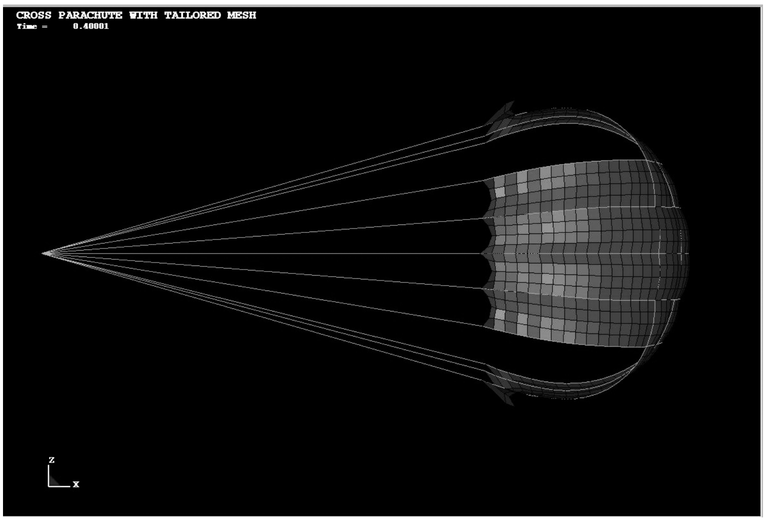

Figure 22

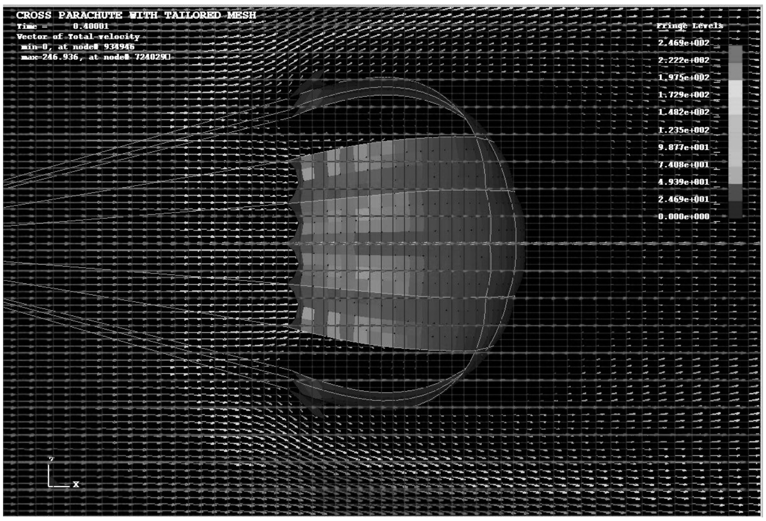

Figure 23

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Appendix 1 – Typical Computer Specification

Pentium III	900 Mhz Dual Processor
Memory	512 Mb
Graphics Card	64 Mb Frame 64 Mb
Storage	36-54 Gb