# THE CASE FOR EXPLICIT FINITE ELEMENT ANALYSIS OF FABRIC SYSTEMS, A COMPARISON TO TEST DATA

A.P. Taylor, Member AIAA
Technical Development Manager
Irvin Aerospace Inc, Santa Ana California 92704

**This paper will present 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 results are presented from the commercially available Explicit FEA package LS-DYNA, as this has been our most successful applications. The presentation of test to simulation comparisons, now available from several projects, will provide the reader with a feel for the level of precision/validation possible with today's simulation tools.**

## Nomenclature

| | |
|---|---|
| FEA | - Finite Element Analysis |
| HOPEX | - H-II Orbiting Plane Experimental |
| HSFD | - High Speed Flight Demonstrator |
| 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. 2-5). Implicit FEA had been introduced earlier for metal parts (ANSYS), but proved virtually useless for fabric systems analysis due to the large deflections involved.

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

Some of our current applications are presented in Reference 1, Presented herein, we concentrate on application of the simulation tool to:

1) Airbags for aircraft/spacecraft recovery
   - Kistler Aerospace
   - NASDA/FHI HOPE-X High Speed Flight Demonstrator (HSFD)
   - US Army Natick, RRDAS Program
2) Unique Nets for a the Launch Stand of a Major US Launch Vehicle

For the applications listed above, we present, herein, comparisons between test and simulation. In general, our approach to testing is to build a test article with as much fidelity as is reasonable, without incurring undue expense. For example, the Kistler data presented is for a 25% scale model, with Fraude number scaling. The HSFD data are for a full-scale model, however, the recovery system parachute is not present in the test. The RRDAS testing is conducted at lighter than full system weight, and again the parachute is missing.

Having developed our test approach, we then construct a finite element model of the test article, and having achieved simulation validation (through correlation) we can then project to the end item configuration by using the same modeling techniques in the test and end item simulations.

The details of achieving test correlation are thoroughly discussed in each section, however, it is important to point out repeatedly, that there are no knobs (fudge factors) in the simulation. Corrections are made in the simulation to account for discrepancies, such as model weight or airbag pressure or venting time, but there are no factors, which are arbitrarily adjusted to produce correlation. Having reviewed this process multiple times, our level of satisfaction with the simulation tool is increasing, and one might suggest (and some have) that eventually, our level of testing might decrease. Certainly, the level of development testing has already been reduced by the ability to evaluate candidate configurations in the virtual world.

## Airbag Applications – Kistler Aerospace

As indicated above, airbag simulations have been completed for several programs. Of these, the Kistler program is thoroughly covered in References 2-5. For instance, Figure 1 presents a correlation of test data to an early simulation for vehicle center of gravity acceleration. This test was with a model of ½ the overall length, with a length-centered center of gravity.

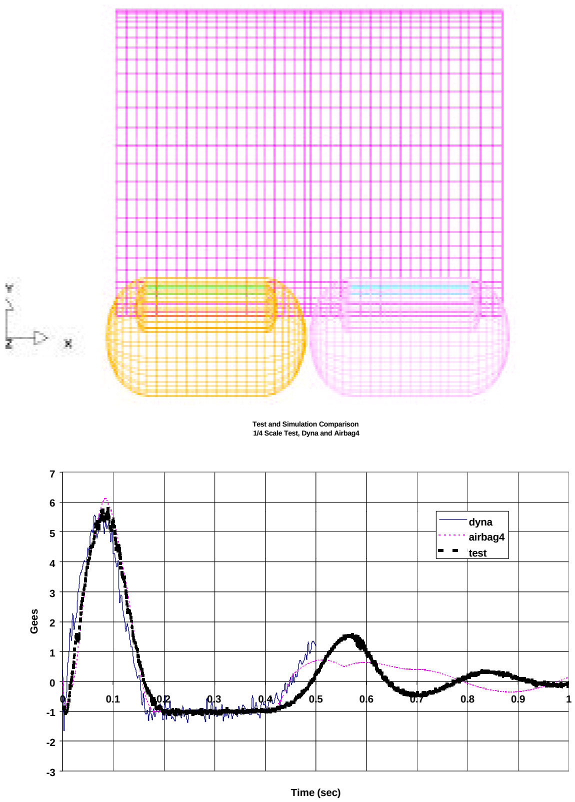


**Figure 1**
**Early Airbag to Simulation Correlation**
**Length Symmetrical Model**

Since that writing, we have completed tests with full-length (scaled) models, and a detailed simulation for comparison (Figure 2). Center of Gravity acceleration, airbag pressures, and vehicle pitch rate time history are all included in our more thorough correlation review.

The additional correlation was under taken to support end item airbag performance improvement. As the vehicle configuration evolved (weight growth), and airbag configuration evolved (number of airbags reduced), we began to predict cases with a negative dynamic envelope (vehicle hits the ground). No cases of ground contact had every been indicated in the test data, though several were observed to come close. Maintaining the testing philosophy presented above, we needed good test to simulation correlation, if our full scale predictions could be trusted.

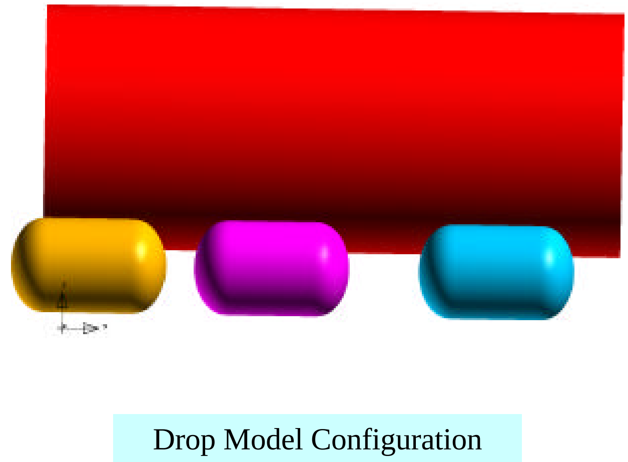


**Figure 2 – FEA Model of Scaled Drop Model**

During construction of the simulation, we discovered/remembered several things. First, the model geometry was slightly different than a simple scaling of the end item configuration, this due to slight adjustments to airbag compartment locations between the time the model was constructed, and the time of test. We therefore, constructed our test simulation to match the drop test article.

Secondly, we discovered an error in our mass accounting program, which computed moment of inertia. This was corrected and the simulation updated.

Finally, we discovered a slight pitch rate due to tip off when the vehicle left the drop rails. The pitch rate itself was not overly critical, as simulations with and without demonstrated. However, the integral of the pitch rate created a 0.3 degree attitude change at impact, from the expected test condition. Adjustment of the vehicle attitude, at impact, was the last required adjustment to provide a reasonable and reassuring level of correlation. Figure 3 presents the pitch rate time history from drop to impact, demonstrating the attitude change. Figure 4 presents the comparison of vehicle pitch rate, test to simulation. Two simulation cases are presented, with and without the adjustment for attitude change, clearly the correlation is better with the attitude adjustment, and easily justified as the pitch rate was a measured parameter.

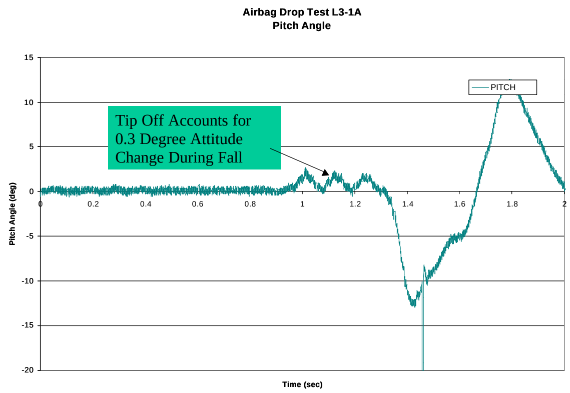


**Figure 3**
**Drop Test Pitch Rate Time History**
**Tip Off Before Impact**

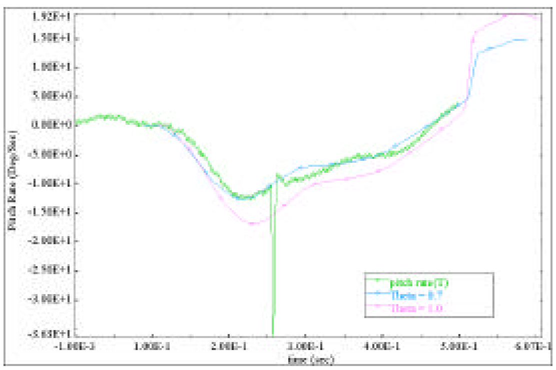

**Figure 4**
**Pitch Rate Time History**
**Corrected for Pitch Attitude Change**

Figure 5 presents center of gravity acceleration time history, for both simulation and test. The comparison is excellent through the peak acceleration. Following peak acceleration, we believe that the difference between linear and non-linear/hysteretic fabric materials accounts for the peak to post peak slight disagreement. Hysteretic fabric models are now available in the simulation tool.

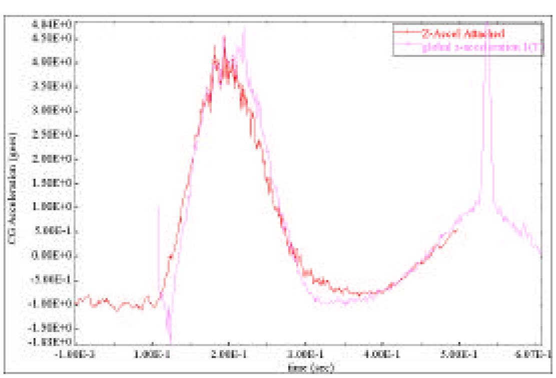

**Figure 5 – CG Acceleration Time History**

The late acceleration peak (simulation curve), indicates a vehicle to ground impact. Both are modeled as rigid bodies in the simulation. While test data does not produce this peak, video and physical evidence indicate a near ground contact. We believe that the difference between rigid to rigid contact (simulation), and flexible to flexible contact (test model to soil) is the only real difference.

Figures 6 thru 8 present pressure time history comparisons – simulation to test. The initial comparisons (Figures 6 and 7) are very pleasing. In Figure 8, which is an inner airbag, we believe that the nonlinear stress/strain curve associated with fabrics is the issue. As this inner airbag is initially rather lightly loaded, the non-linear region of the stress/strain curve is dominant. Following outer airbag deflation, the inner airbag is more highly loaded, and behaves more linearly.

The current release of LS-DYNA would allow for incorporation of fabric non-linearity.

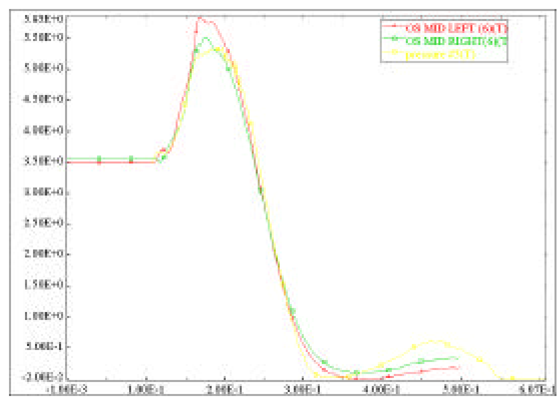

**Figure 6**
**Outer Airbag Pressure Time History**
**Test to Simulation**

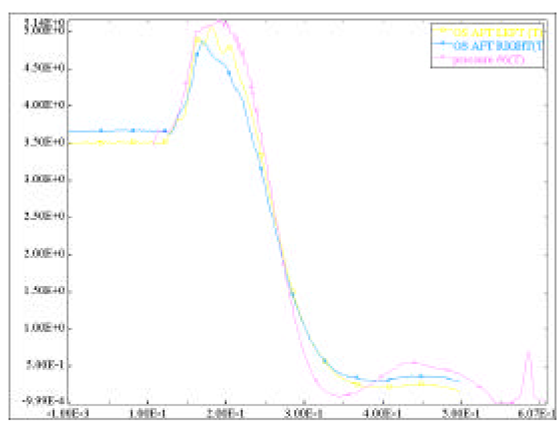

**Figure 7 – Outer Airbag Pressure Time History**

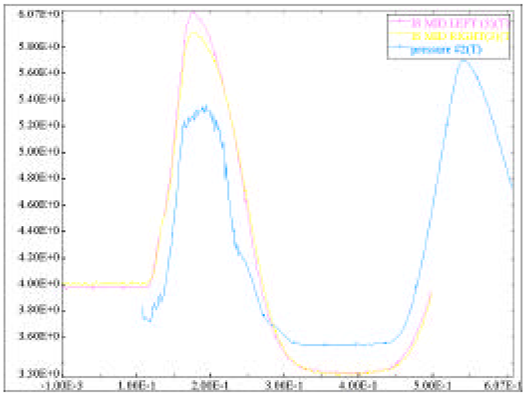

**Figure 8 – Inner Airbag Pressure Time History**

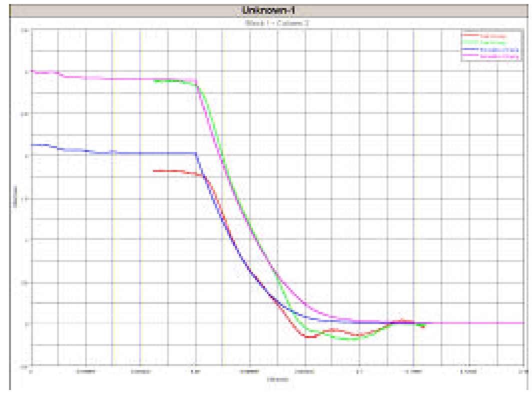


**Figure 10 – Forward Airbag Orifice Calibration**

## <u>NAL/NASDA HSFD Airbag Testing</u>

As indicated above, 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 9 and 10 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).

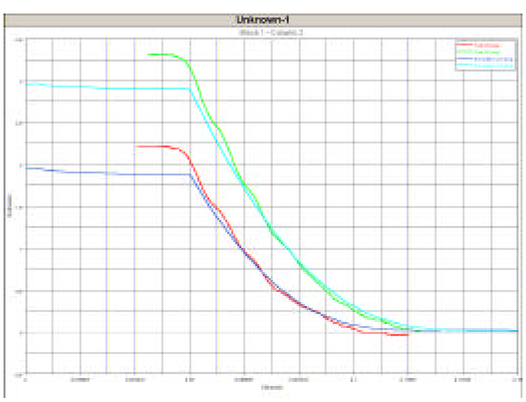


**Figure 9 – Aft Airbag Orifice Calibration**

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 11 presents a view of the drop test model installed in the test track, prior to drop test. Figures 12 and 13 present views of the test impact – note the airbag vent blockage, as illustrated by the soil/dust disturbance. In Figure 12 we present a similar view of vent blockage from an LS-DYNA simulation.

**Figure 11 – Airbag Drop Test Facility**

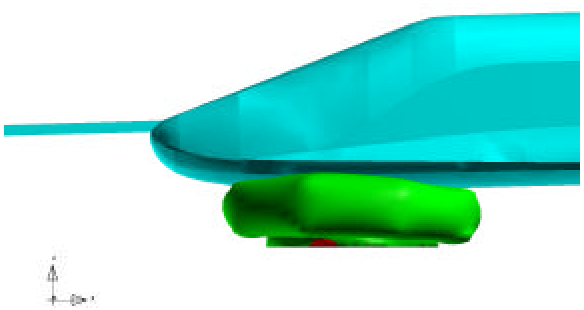

**Figure 12**
**Simulation Result**
**Airbag Vent Blocking Against the Ground**

**Figure 13**
**Drop Test Impact**
**Airbag Vent Blocking Against Ground**

Figures 14 through 18 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.

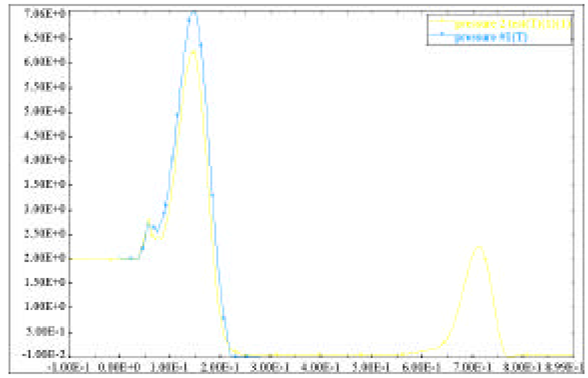

**Figure 14**

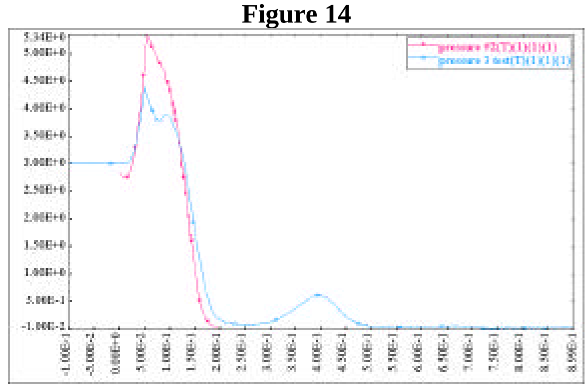

**Figure 15**

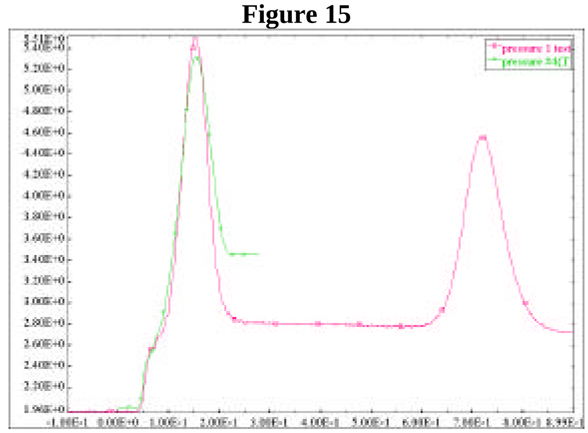

**Figure 16**

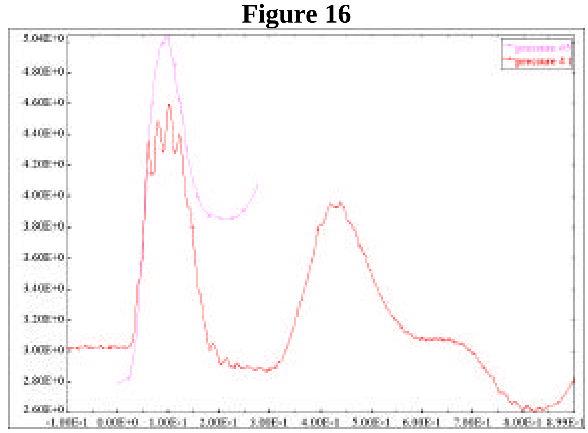

**Figure 17**

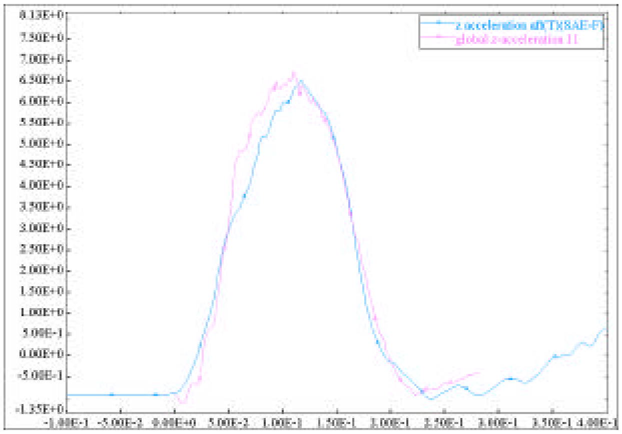

**Figure 18**

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

Figure 15 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 factor that we adjust to improve correlation, rather, we search for physical differences between the drop test model and the FEA analysis.

Figures 16 and 17 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 distorted 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 16, and the peak level and post peak level (lack of correlation) in Figure 17. 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 18 presents a comparison of test and simulation for the vehicle CG acceleration during impact. Similarly, Figure 19 compares the acceleration at 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 envelope of the vehicle during landing.

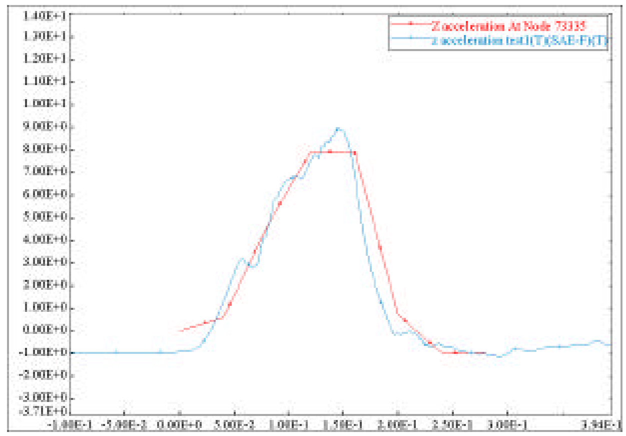

**Figure 19**

**Umbilical Nets – Test Correlation**

Irvin designed, produced and tested heavy webbing nets designed to arrest the motion of fly-away umbilicals on the launch stand of a major Expendable Launch Vehicle (ELV).

The purpose of the nets is to decelerate a large, energetic, and rather fragile umbilical fitting. A portion of the net qualification included the impact testing of an umbilical simulator against the largest (and highest energy) on the system nets.

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 20 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 (manufacturing tolerance) in new nets were tested. 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.

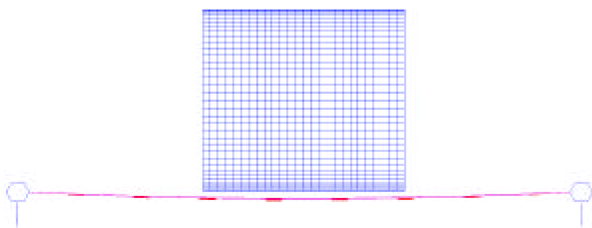

**Figure 20 – FEA Model**

Figure 21 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 22 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 hystericic behavior of fabrics, particularly webbing weaves.

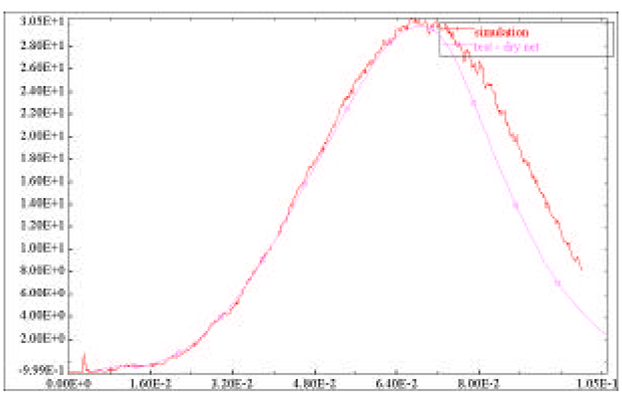


**Figure 21 - Deflection Comparison**
**Dry Net, First Impact, Adjacent Element**
**(Deflection (in) vs time(s))**

Figures 22 and 23 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.

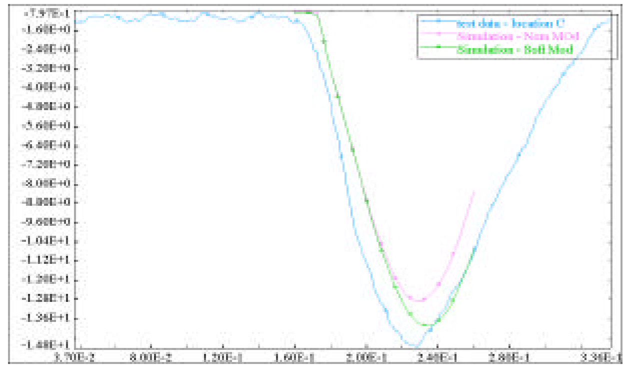

**Figure 22 - Deflection Comparison**
**Dry Net, First Impact, Impacted Element**
**(Deflection (in) vs time(s))**

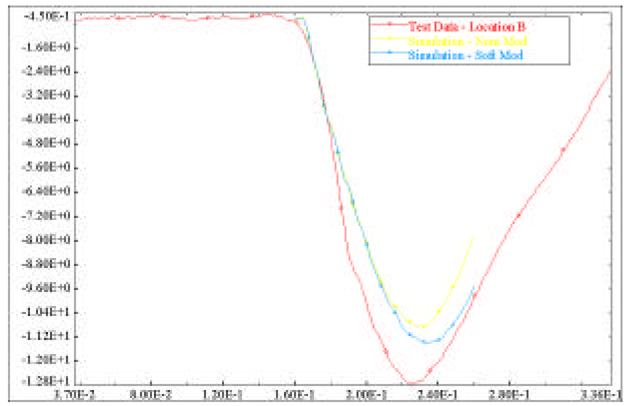


**Figure 23 - Deflection Comparison**
**Dry Net, First Impact, Impacted Element**
**(Deflection (in) vs time(s))**

## Conclusion

The data presented herein are the beginnings of a large database of simulation comparisons at Irvin. At the time of this writing, additional tests are being performed, and other tests are not fully analyzed.

We have however, concluded that the simulation code ad techniques represent a substantial and impressive ability to simulate these events.

Current and future work (on several programs) will include further definition of quasi-static load cases and failure criteria, as well as expanding applications of dynamic simulation.

## References


1. Taylor, A.P., “Explicit Finite Element Analysis of Fabric Systems, Real World Applications” 16th Aerodynamic Decelerator Systems Technology Conference, AIAA - 2001-2002
2. Taylor, A.P., and Delurgio, P.R., “An Overview of the Landing System for the K-1 Launch Vehicle, Parachutes and Airbags” AIAA 97-1515
3. Gardinier, D. and Taylor, A.P., “Design and Testing of the K-1 Reusable Launch Vehicle Landing System Airbags” AIAA 99-1757
4. Fallon, E. and Taylor, A.P., “Landing System Design Summary of the K-1 Aerospace Launch Vehicle” AIAA 99-1720
5. McKinney and Taylor, “Use of LS-Dyna to Simulate the Airbag Landing Impact Attenuation of the Kistler K-1 RLV”, 5$^{th}$ International LS-DYNA Users Conference 1998