Evaluation of LS-DYNA® Corpuscular Particle Method – Passenger Airbag Applications

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Abstract

A uniform pressure method, i.e. no pressure variation on bag surface and location, in LS-DYNA has been commonly used to simulate airbag deployment and interaction of airbag with the occupants. Another newly developed LS-DYNA CPM (Corpuscular Particle Methodology) has gained recognition and acceptance recently because it considers the effect of transient gas dynamics and thermodynamics by using a particle to represent a set of air or gas molecules and then a set of particles to represent the entire air or gas molecule in the space of interest. This LS-DYNA feature has been studied in side impact airbag applications, and it is being further investigated in passenger side airbag applications to gain confidence in its application.

In this paper, a comprehensive set of sixty-liter tank tests, airbag static deployment tests, and rigid linear impactor tests with both the first stage and dual stage deployments are conducted and simulated to validate the CPM method. The correlations start with well controlled inflator closed and vented tank tests to verify the inflator characteristics from a supplier, mainly the mass flow rate and temperature curves. In the tank test validation, the steel tank's heat convection coefficient is the only parameter being adjusted to match the tank pressure in deployments. To ensure model fidelity, these validated inflator characteristics must continue to be employed into the static/dynamic airbag deployment simulations without applying any scaling factors. Other airbag fabric related parameters, such as the fabric heat convection coefficient and leakage coefficients, can be adjusted within its range, to correlate the airbag pressure measured in tests.

With the systematic approach to validate and correlate the impact tests, it results in good agreements with the overall airbag internal pressure and impactor deceleration for the suite of linear impactor tests conducted. The necessary modeling techniques to achieve a highly correlated airbag finite element model using LS-DYNA CPM method were identified in the process and the CPM can be applied to evaluate occupant performances with confidence.

Introduction

The airbag CV (Control Volume) method has been widely used with good correlations for the events when an occupant impacts an already inflated airbag[1, 2]. For out-of-position (OOP) airbag simulations [3]; however, the CV method is less accurate in predicting the occupant-to-airbag responses. To improve the correlations of an occupant impacting an inflating airbag, a CPU intense ALE (Arbitrary Lagrangian Eulerian) [4] method has been developed. In recent years, a numerical corpuscular particle methodology has been developed and gained more attention and acceptance for airbag deployment applications [2-8]. The particle method considers the effect of transient gas dynamics and thermodynamics by using a particle to represent a set of finite air or gas molecules. Then, a set of particles is used to embody the entire air or gas molecules in the space of interest [2]. This particle method has been documented [2] as an improvement over the CV method with similar accuracy compared with ALE method which requires much more CPU resource.

Side impact airbag (SIAB), passenger side airbag (PAB), and out-of-position airbag deployment are typical cases that occupants may come into contact with an inflating airbag. For SIAB, the airbag is mounted on the side of a seat and is much closer to the occupant and the surrounding structure while it is inflating. For the PAB, a similar situation can happen when the Hybrid III 5th female dummy is in full forward seating position or when a child dummy is tested with the NHTSA out-of-position procedure.

The Corpuscular Particle Methodology (CPM) has been validated and documented for the side impact airbag applications[8]. In this report, we are extending our study to the passenger side airbag.

The Validation Approach

A sixty liter inflator closed and vented tank tests were conducted first followed by a comprehensive set of rigid linear impactor tests with various impactor masses and impact speeds. Those masses and speeds are determined to comprehend the dummy head mass and the relative closing speed of a dummy to an inflating PAB upto 35 mph impact. It is critical to design the impact tests with various levels of impact energies so that the delivered and correlated airbag model is not tuned to a specific impact and has a robust response for its wide variety of applications.

The CV (Control Volume) airbag model received from the suppliers was converted into CPM model based on the best practices learned from our previous side impact airbag study. This CPM model is used to simulate the designed impact tests before they were conducted. The airbag fabric's heat convection coefficient is the only parameter being adjusted (within the documented engineering standard range) to achieve a final correlated model.

The conducted the inflator closed tank test is to characterize and determine the inflator mass flow rate and temperature curves, which are the necessary inputs for finite element simulations[8]. After receiving these inflator information, both closed and vented tank physical tests were correlated using particle method to ensure fidelity of the received inflator characteristics.

To accurately capture the heat transfer between the gas and the enclosed tank surface, the heat loss through conduction with the steel tank surface should be incorporated into the calculation of the inflator mass flow rate and temperature change. Since the essential tank tests are conducted without the complication of airbag deployment, these derived inflator mass flow rate and temperature curve inputs should not be altered and scaled in a later airbag deployment simulations.

After simulating and then confirming the inflator tank test results, we then proceeded to simulate the airbag static deployment and impact tests. In static deployment, the bag pressure profile is simply the function of the fabric heat convection coefficient, fabric leakage parameter, as well as the leakage through the seam. These fabric panel's parameters can be then determined from such a test.

Next, the airbag pressure and impactor deceleration of the linear impact tests were correlated with the set of fabric parameters determined from the static deployment simulation. It is very important to correlate finite element model to both the impactor deceleration and the airbag pressure so that we can gain insight of the model fidelity. These set of fabric parameters should be continued to be employed when applying the CV method if it is desired to apply it for occupant simulations[8]. The recorded pressure tube data from the tests may not represent the average bag pressure in its unfolding phase. However, the pressure data should be relatively close to the average bag pressure when the bag is fully inflated. The measured pressure data will provide critical information of the test repeatability and give addition data point to the numerical correlation. Otherwise, the impactor deceleration history is the sole quantifiable comparison and provide less guidance for further improving the finite element model.

Baseline Passenger Airbag Finite Element Model

The airbag finite element model, a traditional control volume (CV) airbag, had been correlated to three physical tests: one static deployment with dual stage inflator and two relatively low speed Tuffy impact tests. In the validation report, the airbag pressure and the Tuffy impactor's deceleration were compared with the tests to demonstrate the model's fidelity. Correlations of the model are shown in Figures 1, 2, and 3, and the simulations are in good agreement with the tests.

These correlations were simulated using an older version of LS-DYNA SMP R7 4.1.2. We repeated the simulations using the version of MPP 971 R6.1.2 on the HPC machines. The correlations are shown in Figures 4, 5, and 6, and they also show good correlations. The CV model predicted a 4G peak Tuffy impactor acceleration, one G lower comparing with the 5 m/s test, and the model estimated 13G peak acceleration, three G higher, for the 6.72 m/s impact test.

The PAB subcomponent finite element model used for correlation is shown in Figure 7. It includes the windshield, IP surface, airbag housing, and the airbag model itself. The airbag finite element mesh fitted in the airbag housing is a scaled down model from the airbag's reference geometry, as shown in Figure 7 (triangular element mesh is used). This model correlated reasonably well with the tests' accelerations. However, in the simulations the lower portion of the Tuffy model rotated toward the glove box region and bottomed out at the lower portion of the bag. This bottoming out in the simulation caused a sudden rise of the Tuffy deceleration which was not observed in the physical test.

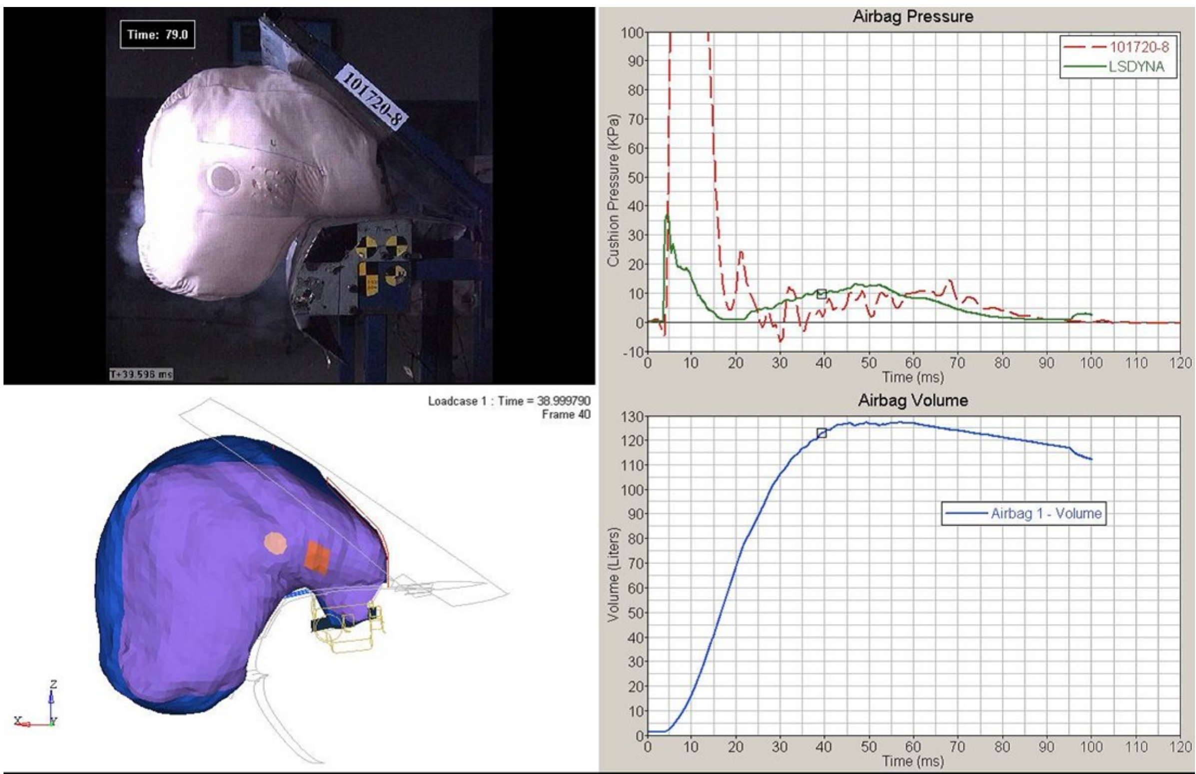


Figure 1. Dual stage static deployment correlation of the delivered PAB model.

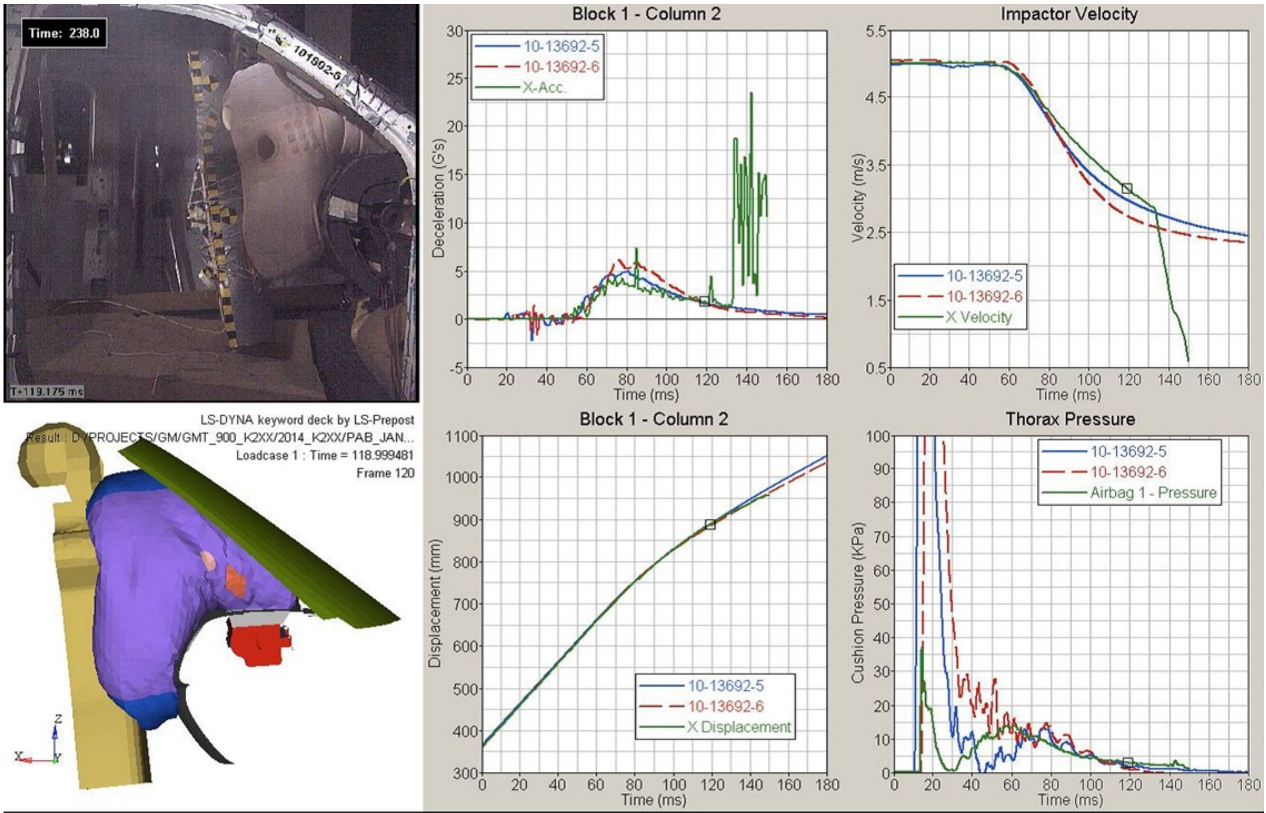


Figure 2. Thirty four kilogram Tuffy model impacting PAB with a velocity of 5.0m/s.

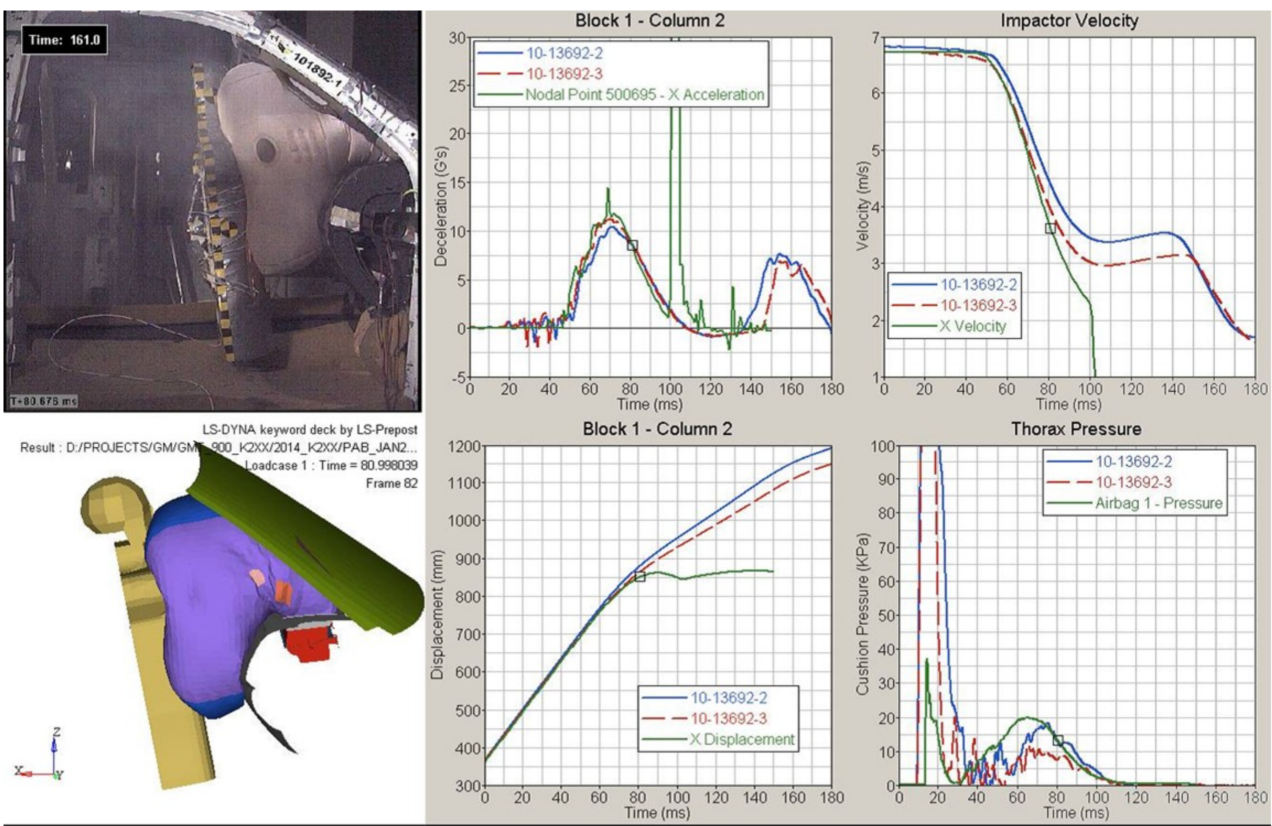


Figure 3. Thirty four kilogram Tuffy model impacting PAB with a higher velocity of 6.72m/s.

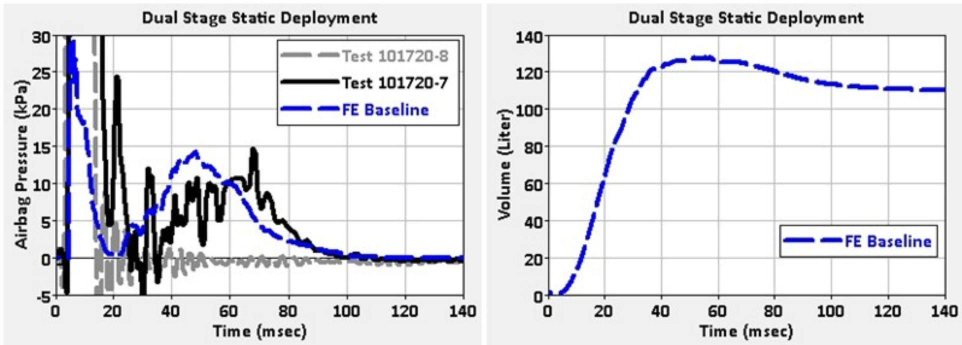
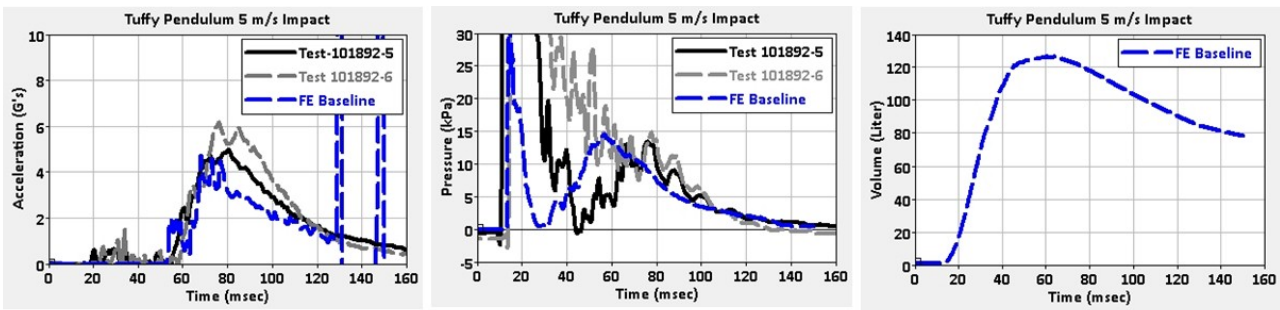
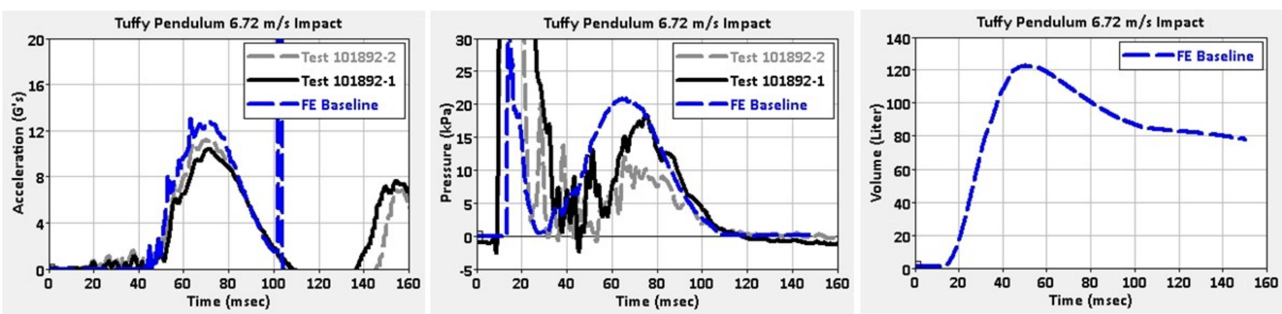


Figure 4. Dual stage static deployment correlation of the delivered PAB finite element model using GM internal HPC and LS-DYNA 971 version R6.1.2.



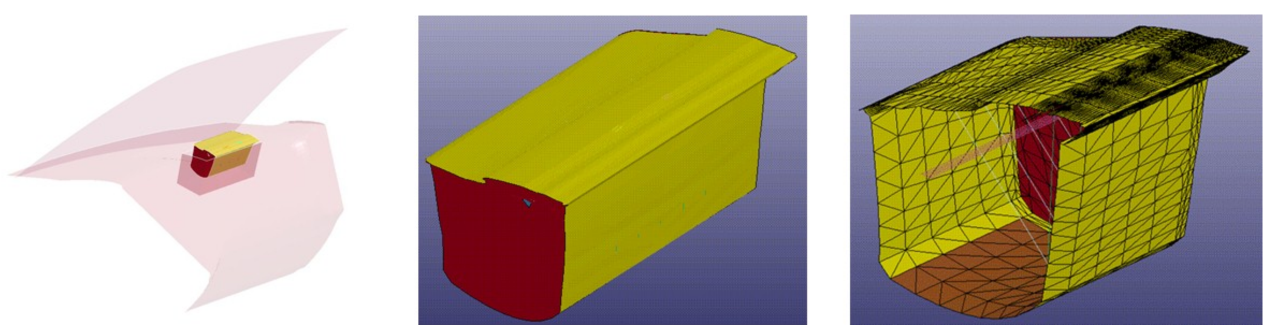
(a)Tuffy impactor deceleration (b) Airbag internal pressure (c) Airbag volume

Figure 5. Tuffy impact test with a velocity of 5.0m/s of the delivered PAB finite element model using GM internal HPC and LS-DYNA 971 version R6.1.2.



(a)Tuffy impactor deceleration (b) Airbag internal pressure (c) Airbag volume

Figure 6. Tuffy impact test with a velocity of 6.72 m/s of the delivered PAB finite element model using GM internal HPC and LS-DYNA 971 version R6.1.2.



(a) IP surface and PAB (b) PAB model (c) Half of the PAB mesh

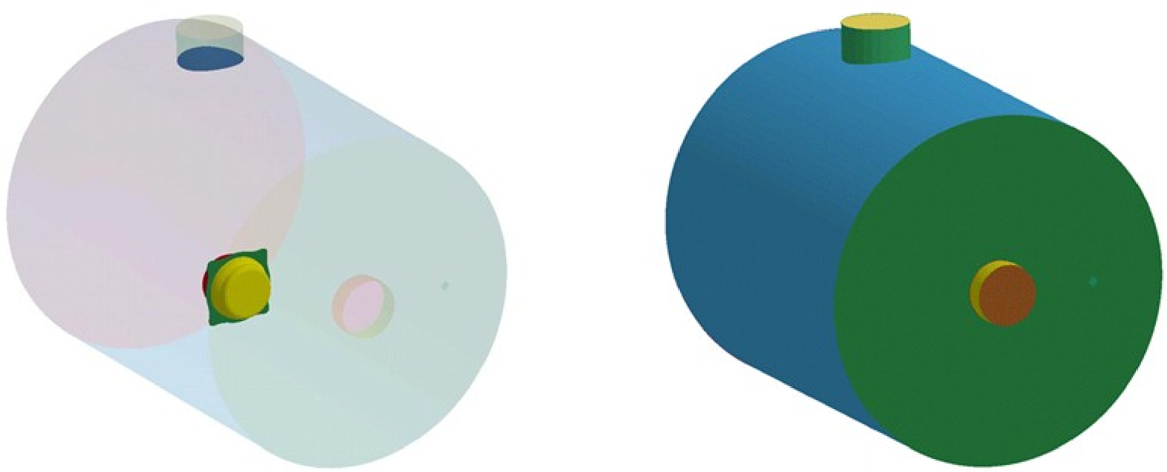
Figure 7. The delivered passenger airbag finite element model and instrument panel surface for K2XX vehicle, (a) Passenger airbag model placed inside the airbag housing and K2XX IP surface, (b) the PAB finite element model, (c) the PAB mesh is a scaled down mesh from the reference geometry.

Tank Tests

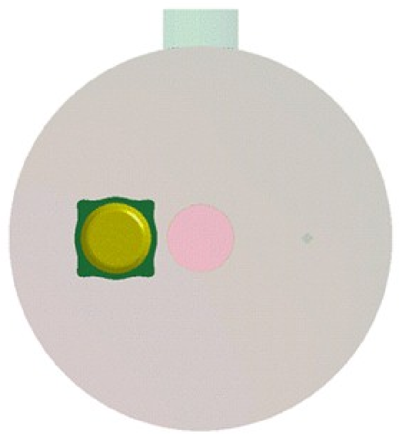
As a standard procedure from the side impact airbag study, the inflator closed tank test is conducted, and the pressure is measured in order to generate the inflator's characteristic temperature and mass flow rate curves, the test apparatus is shown in Figure 8. Initially the inflator curves provided were generated without considering the heat loss through the steel tank and we cannot reproduce and validate the tank pressure curves with high fidelity in simulation. The inflator mass flow rate and temperature curve were then regenerated by considering the heat loss of the steel tank.

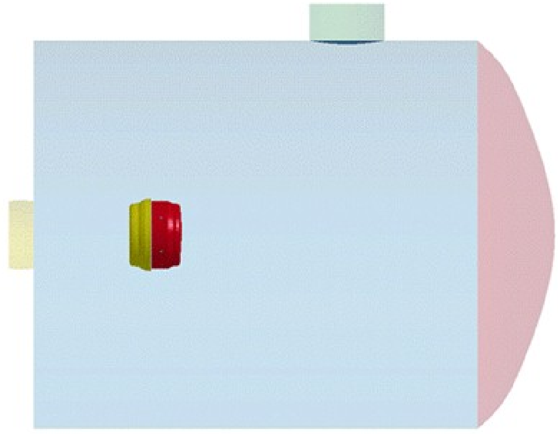
After obtaining the improved inflator mass flow rate and temperature curves for both single stage and dual stage deployments, we proceed to simulate the tank tests with the heat convection coefficient, parameter of HCONV in LS-DYNA, of 3.5x10-7 W/mm^2K. As show in Figure 9, this heat convection coefficient seems to result in better correlated pressure profiles for both single stage and dual stage deployments and for both the open and closed tank tests. The gas temperature inside the tank was not compared due to thermocouple's low response time.

There are initial air molecules inside the tank, which need to be included in the simulation to accurately represent the existing air molecules before the test. The rule of thumb in determining the number of particles to represent the air and the gas is to obtain the ratio of the total mass of the air and gas and then formulate the mass of each gas and air particle to be equal. For the particle method of closed tank test simulation, the number of particle can be relatively small (10k particles will be fine for such a purpose). A small number of particles will not influence accuracy of the closed tank simulation since there are no gas particles leaking out of the tank and the particles can reach equilibrium state with very few cycles, e.g., 500 cycles. For the vented tank simulation, a larger number of particles will slightly lower the simulated peak pressure and, of course, with has a higher CPU cost.



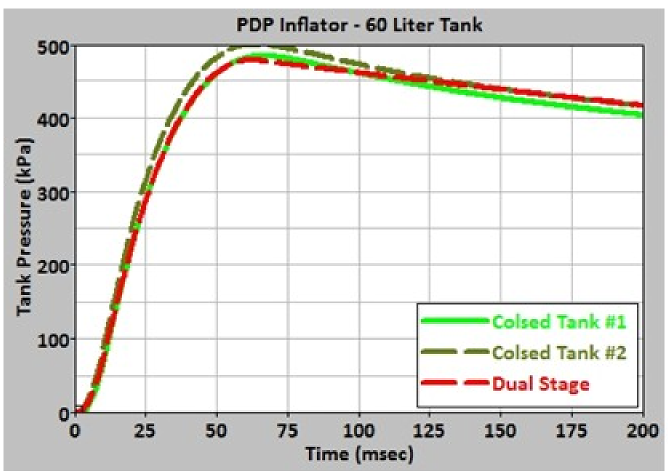
(a) Transparent view of the FE model (b) Exterior view of the FE model

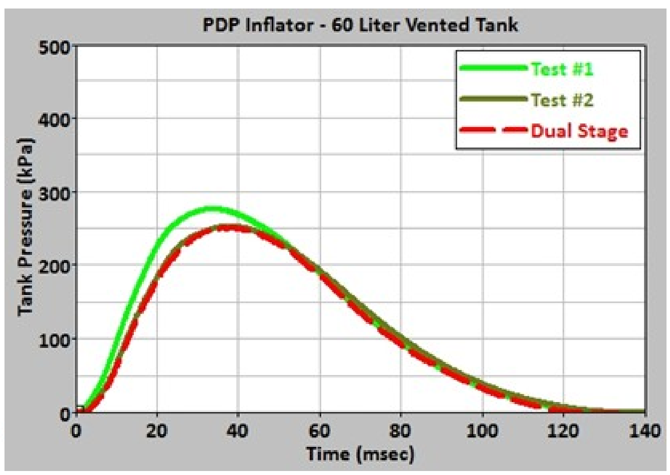




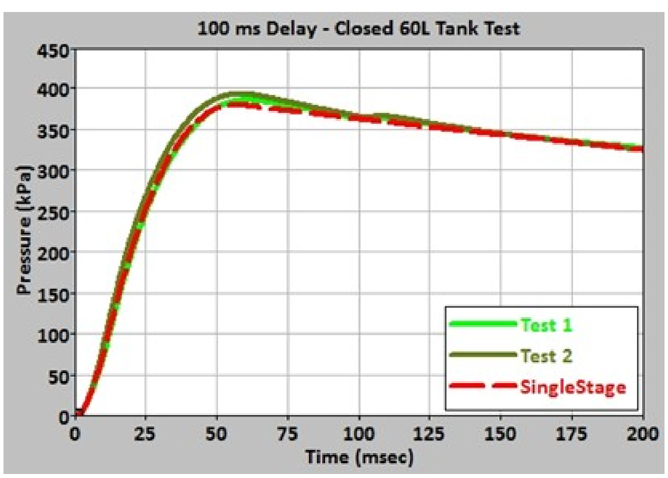
(c) Front view of the FE model (d) Side view of the FE model

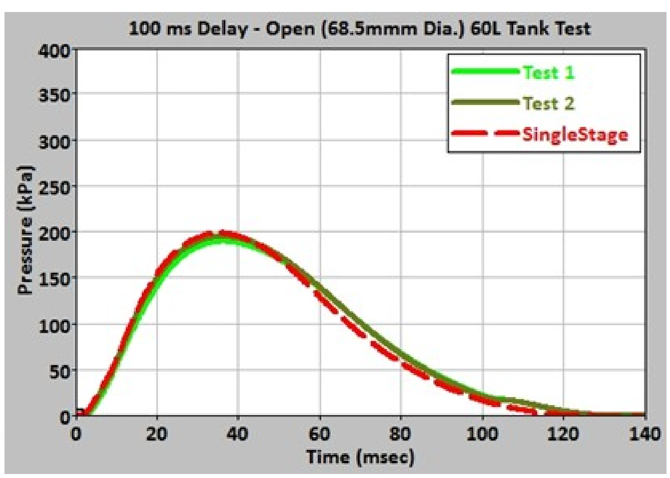
Figure 8. 60 liter tank finite element model used for closed and vented tank tests. (a) Transparent view, (b) exterior view, (c) front view, and (d) side view.





(a) Closed tank test for dual stage (b) Vented tank test for dual stage





(c) Closed tank test for 100msec delay (d) Vented tank test for 100msec delay

Figure 9. Tests of closed and vented tank tests and results from finite element simulations using particle methods. (a) Closed tank test and simulation for dual stage inflator, (b) vented tank test for dual stage inflator, (c) closed tank test for 100msec delay inflator, and (d) vented tank test for 100msec delay inflator.

Squashing Airbag Into The Housing & Its Static Deployment

The delivered PAB mesh was geometrically scaled down from the airbag reference geometry excluding the two tethers (a reference geometry is the state of a fabric panel when there is no existing stress in the mesh) and fitted into the airbag housing. Triangular membrane elements, very small scaled down elements, were used by the supplier to model the panels. The triangular element formulation will cause the airbag membrane behave stiffer than the quadratic element formulation. And, the fabric compressed stress feature cannot be turned on in the simulations when adopting such a scaled down method since the tiny elements will have very large initial compressed stresses. To improve the model quality, we regenerated a 4 nodes quadratic airbag model instead of the scaled-and-fitted model so that we can better simulate the deployment process.

For this study, we did not fully exercise the state of the art folded airbag since the objective to validate the CPM method. We simply squashed the PAB reference geometry into the airbag housing, adopted the methodology developed by Yunqiang Li (private conversation). The squashing method consists of numerous flat plates which enclose the PAB's initial reference geometry. Each of the plates will then translate or rotate to push the fabric panels into the housing using simulation.

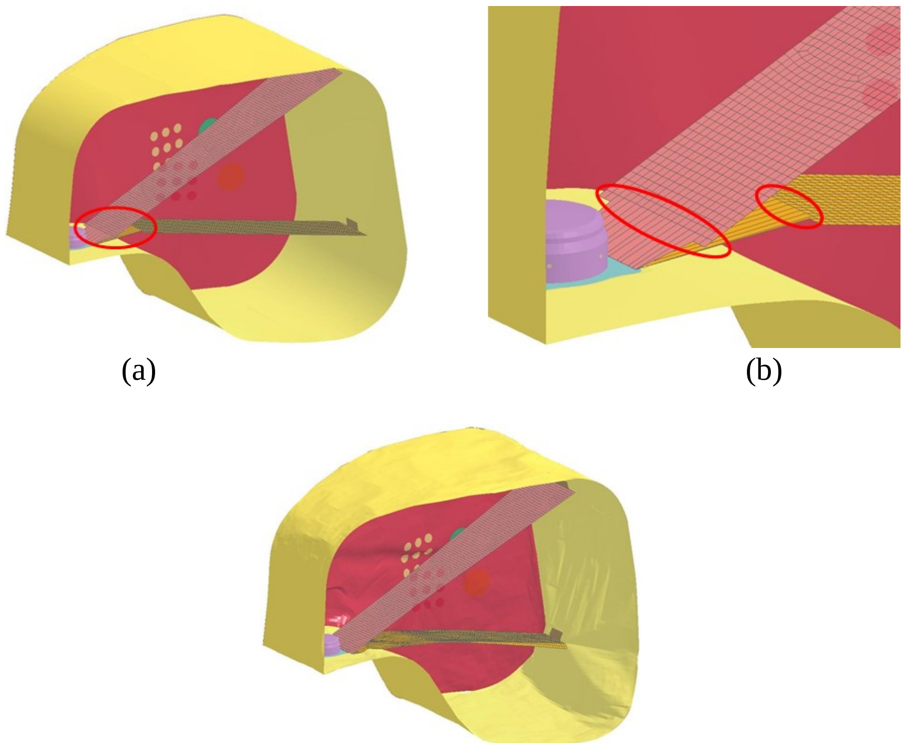
The two tethers controlling the front panel shape and airbag volume were modeled as 1 D discrete elements in the original model. Tether lengths are designed for the best protection of the occupant by providing a proper airbag and occupant interaction with an optimized bag pressure and profile in impacts. Length of the two tethers are shorter than the distance from the inflator disk to the airbag front panel in its reference geometry. To compensate for the length difference, the first row of the tether segments (at the inflator disk end) was overly stretched, as shown in Figure 11. Those segments developed huge amount of initial stress in the squashing process and caused the simulation to terminate.

To resolve this issue, these overly stretched nodes (circled in Figure 10(b)) were moved toward the inflator disk, as shown in Figure 10(c), using the prescribed motion function in LS-DYNA. Afterward, this new airbag mesh was compressed and fitted into the airbag housing by the squashing method. In all these LS-DYNA simulations, the fabric material should refer to the airbag reference geometry and be capable of resisting compressive stress to prevent the elements from being overly compressed into very small elements. Because those small elements will develop huge initial stress in deployment simulation and cause numerical instability.

The sequence of squashing the airbag model is depicted in Figure 11. To overcome skewed airbag deployment as we have experienced after such a process, we further improved it by constraining lateral movement of the airbag's mid-plane nodes such that a more symmetric squashed airbag can be achieved. This symmetry will push the airbag straight forward in the deployment process. Another special care while compressing the airbag into the housing is to leave enough gap at the inflator nozzles for the air particles to discharge into the bag for the CPM method. This can be easily accomplished by defining a larger contact thickness (e.g., 5mm) for the inflator disk part in the squashing simulation. The final compressed airbag is shown in Figure 11(d).

To obtain a proper fabric heat convection coefficient, we designed a first stage only deployment test with the vents sealed. With a smaller bag pressure from the first stage deployment, the sewn seam will not be overly stretched such that no gas particles will leak out through the seam. Then, the bag pressure reduction from such a vent-sealed bag is mainly from the heat transfer through the fabric surface. By adjusting the heat convection coefficient of the fabric, well correlated bag pressure profiles for both the first stage deployment with sealed vents (shown in Figure 12(a)) and the dual stage deployment with the functioning vents (as shown in Figure 12(b)) were achieved. The heat convection coefficient used in the two simulations was determined to be $2*10^{-7}$ after a few numerical iterations.

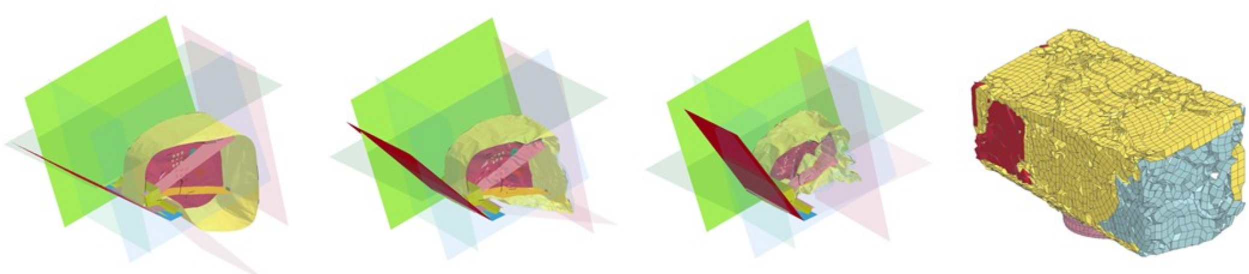
We also sought to have a better correlated LS-DYNA fabric material model. The main improvement of the fabric model was that the fabric material's unloading characteristic was included. In simulating the first stage deployment of a vent-sealed bag, it was noted that the bag volume expanded a bit faster and the deploying bag drops down from the windshield to the IP surface sooner when the unloading curve was not included, as depicted in Figure 13. The first stage deployment of a vent-sealed bag including material's unloading characteristic in simulation at 150 msec is overlaid with the test in Figure 14.



(a) (b)

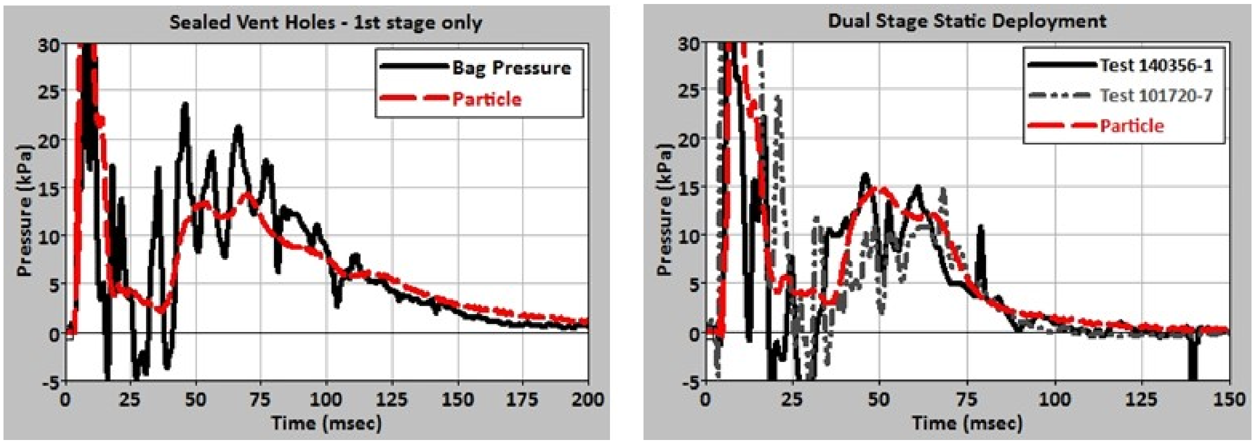
(c)

Figure 10. (a) The initial reference geometry of the PAB, (b) the second row of the nodes on the tethers near the inflator base were pulled toward the base at the end of the simulation, (c) the nodes that were being pulled toward the base of inflator to reduce the amount of stretch.



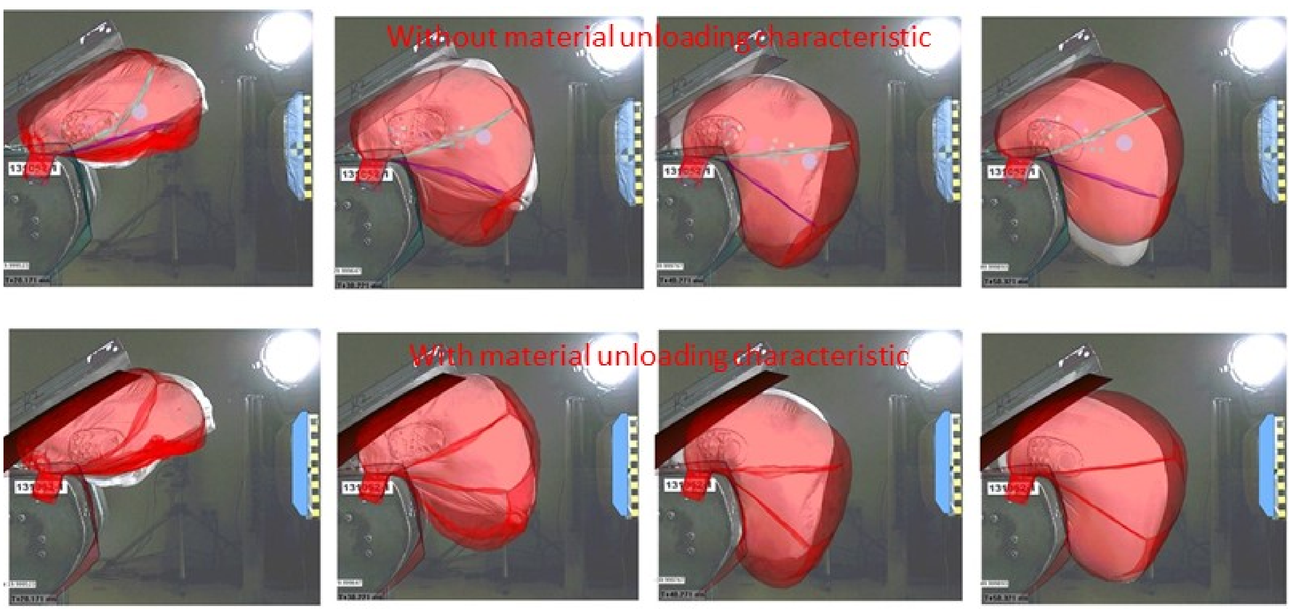
(a) (b) (c) (d)

Figure 11. (a) Airbag enclosed by the plates before squashing, (b) in the mist of squashing, (c) further into the squashing process, (d) squashed and compressed airbag.



(a) (b)

Figure 12. (a) The PAB first stage deployment with the vent sealed, (b) dual stage static deployment.



(a) 20 msec (b) 30 msec (c) 40 msec (d) 50 msec

Figure 13. Comparison of the first stage deployment sequence of a vent-sealed airbag with (figure on the bottom) and without (figures on the top) modeling of the fabric material's unloading characteristic.

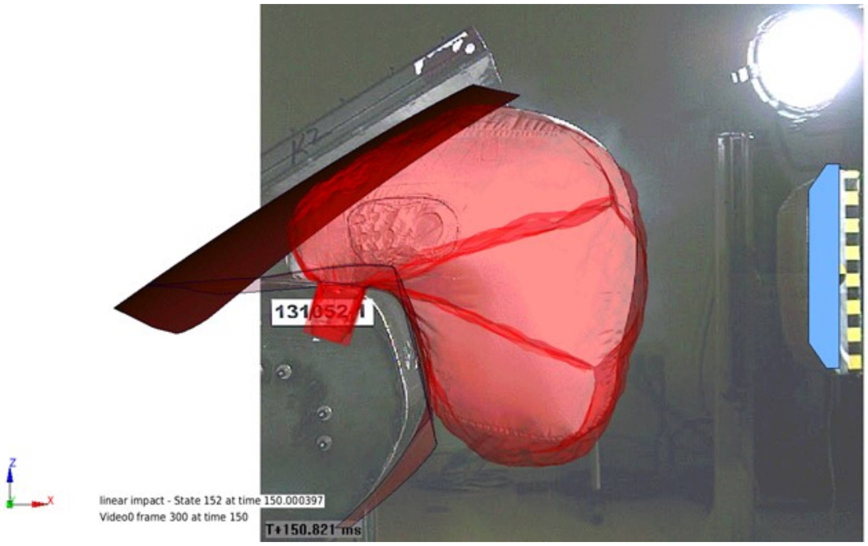


Figure 14. Good agreement with the test for the first stage deployment of a sealed vents airbag at 150 msec.

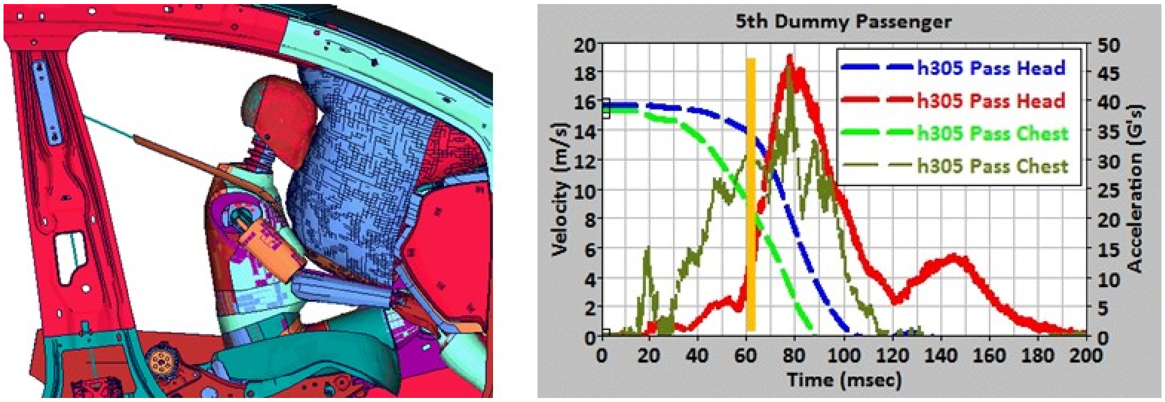
Linear Impactor Tests

In order to determine the proper linear impactor masses and velocities for our test matrix, we looked into the passenger head and chest velocity and acceleration histories of a sedan sled model, shown in Figure 15(a). The passenger airbag starts to contact and interact with the 5th percentile female Hybrid III dummy at 60msec, as shown in Figure 15(a). At that interacting time, the head has an impact velocity of 14 m/s, while the chest with the constrained of a seatbelt has an impact velocity of 9 m/s. The 5th percentile female head is about 5 kg, and her upper body mass is about 22 kg. To comprehend the impact situation, we then decided to conduct the tests tabulated in Table 2 based on the availability and capability of the test lab.

Correlations of the impactor acceleration and the overall airbag pressure of the PAB impact tests are shown in Figure 16. Peak acceleration of the tests has a very wide spread, ranging from 2G to 60G. Good acceleration correlations are achieved for the suite of impact tests which further validate the particle method in LS-DYNA. The pressure tube was inserted at the vicinity of the inflator disk and cannot represent the overall bag pressure when gas is injected into the airbag chamber, hence, the pressure comparisons in Figure 16 are for reference only.

Table 1. Linear impactor test matrix

Impact Test #	**Inflator Type**	**Impactor Mass (kg)**	**Impact Speed (m/s)**
1	1st stage only	19.9	5
2	Dual stage	19.9	5
3	Dual stage	19.9	6.7
4	Dual stage	7.1	9.5
5	Dual stage	7.1	7.0



(a) (b)

Figure 15. (a) GMX353 passenger simulation at 60msec, (b) The velocity and acceleration histories of the passenger's head and chest.

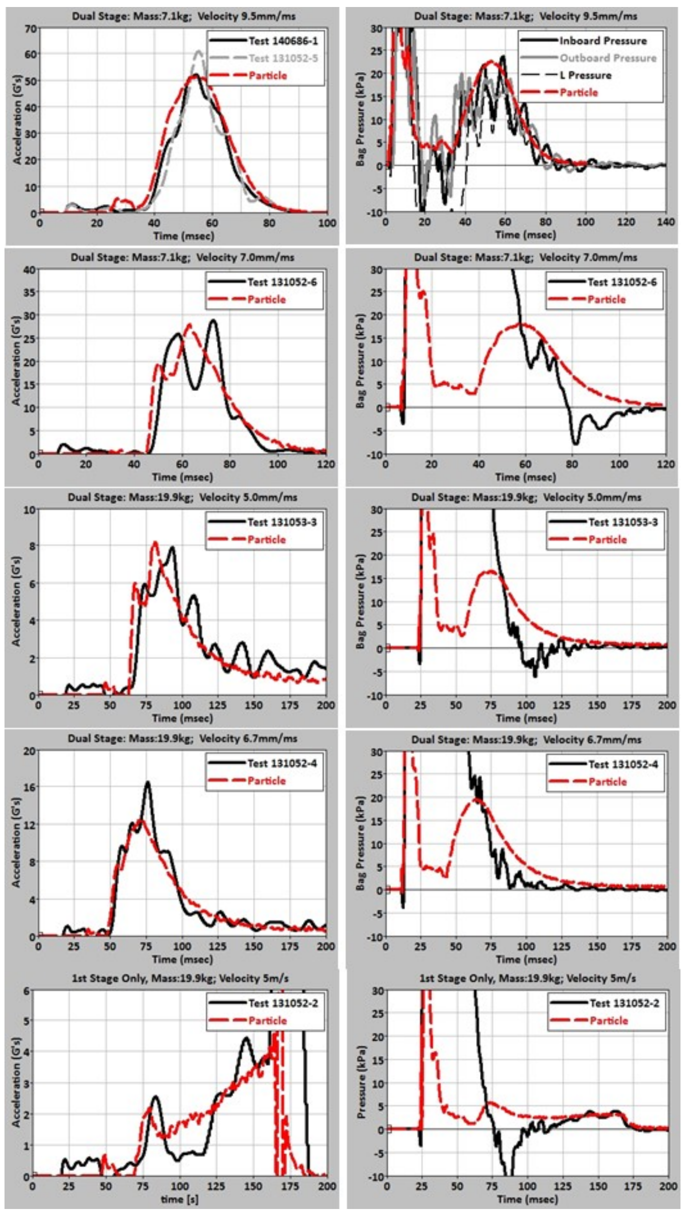


Figure 16. Impactor deceleration and airbag pressure correlation of the dual stage and 1st stage linear impactor tests.

Summary

This LS-DYNA particle method for the passenger airbag has been fully investigated and validated against a comprehensive set of closed and open tank tests, airbag static deployment tests, and airbag rigid linear impactor tests. The correlations start from the closed and vented tank tests to verify the inflator characteristics, i.e., the mass flow rate and temperature curves. The inflator characteristics were employed into static airbag deployment simulation without applying any scaling factor. In correlating the static deployment for both the first stage and the dual stage deployments, the airbag fabric heat convection coefficient was determined. It should be noted that this was the only parameter which was tuned to match the tests.

Using this systematic validations and correlations approach without applying other tuning factors result in a good match of a wide range of impactor decelerations. This study allows the LS-DYNA CPM to be applied with much higher level of confidence in airbag applications, and the necessary modeling techniques needed to achieve a highly correlated model are identified.

Acknowledgements

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References

1. Lee, J. K., Ha, W. P., Lee, J. H., Chae, D. B., and Kim, J. H., "Validation Methodology on Airbag Deployment Process of Driver Side Airbag", 21st International Technical Conference on the Enhanced Safety of Vehicles, June 15-18, 2009, International Congress Center Stuttgart, Germany.
2. Hirth, A., Haufe, A., and Olovsson L., "Airbag Simulation with LS-DYNA Past – Present – Future", 6th European LS-DYNA users' conference, Frankethal, Germany, 2007
3. Lian, W., Bhalsod, D., and Olovsson, L., "Benchmark Study on the AIRBAG_PARTICLE Method for Out-Of-Position Applications", 10th International LS-DYNA Users Conference, Dearborn, MI, USA, June 8-10, 2008
4. Zhang, H., Raman, S., Gopal, M., and Han, T., "Evaluation and Comparison of CFD Integrated Airbag Models in LS-DYNA, MADYMO and PAM-CRASH", 2004 SAE World Congress, Detroit, Michigan, March 8-11, 2004, SAE 2004-01-1627
5. Teng, H., Wang, J., and Bhalsod, D., "The Recent Progress and Potential Applications of Corpuscular Method in LS-DYNA", 11th International LS-DYNA Users Conference, Dearborn, MI, USA, June, 2010.
6. Zeguer, T., Feng, B., and Coleman, D., "Gas Dynamic Simulation of Curtain Airbag Deployment Through Interior Trims", 7th European LS-DYNA users' conference, Bamberg, Germany, 2008
7. Freisinger, M., Hoffmann, J., and Stahlschmidt, S., "Investigation of the Early Inflation Characteristics of a Complex Folded Knee Airbag with the New Corpuscular Method in LS-DYNA", 6th European LS-DYNA users' conference, Frankethal, Germany, 2007
8. Lin, C., Cheng, Y., and Wang, J., "Evaluation Of LS-DYNA Corpuscular Particle Method For Side Impact Airbag Deployment Applications," 13th International LS-DYNA Users Conference, June 8-10, 2014