Investigation of the Early Inflation Characteristics of a Complex Folded Knee Airbag with the New Corpuscular Method in LS-DYNA

M. Freisinger[1], J. Hoffmann[1], S. Stahlschmidt[2]

[1]Toyoda Gosei Europe NV, Saarbrücken, Germany

[2]Dynamore GmbH, Stuttgart, Germany

Abstract:

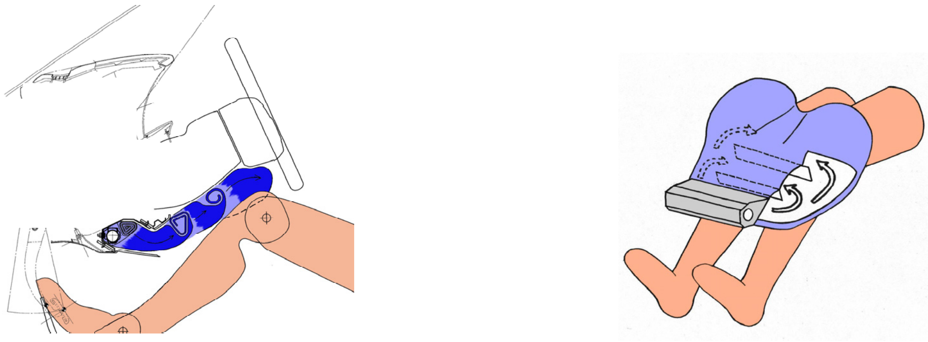
To address the challenging out-of-position (OoP) load case with Ls-Dyna, the corpuscular (particle) method has been recently developed together with the advanced finite element (FE) airbag simulation method. Within this study, an attempt is made to integrate this advanced airbag simulation method into a frontal knee airbag development process. The deployment kinematics of a complex driver knee airbag (DKAB) is also simulated using the control volume method. A dynamic airbag impactor test scenario serves as the validation goal of the airbag kinetic energy absorption properties and the unfolding kinematics, especially in the early phase of inflation. A passenger airbag (PKAB) design with different geometry can only be derived numerically with the help of numerical simulation. Finally, its mechanical properties (energy absorption and deployment characteristics) are verified by real dynamic impactor tests.

Keywords:

OoP, Gas flow, Corpuscular method, Knee airbag

1 Introduction

Knee airbags are designed to protect the lower extremities from hard obstacles. During a frontal crash, the cushion has to position between the steering column and the occupant's lower extremities on the driver's side (see Figure 1a). After airbag ignition, the upward unfolding process along the steering column cover is supported by the redirection of the gas flow at internal tethers as shown in Figure 1b below.



(a) Deployment along dummy leg contour (b) Gas flow redirection at tethers

Figure 1: DKAB deployment path between steering column and occupant knee and tibia

As a result, the DKAB cushion deploys initially along the steering column cover and the occupant's tibia and knee. The technology outlined above and applied on the passenger's side leads to deployment along the glove compartment since the PKAB is supported below the lower edge of the instrument panel (see Figure 2 below).

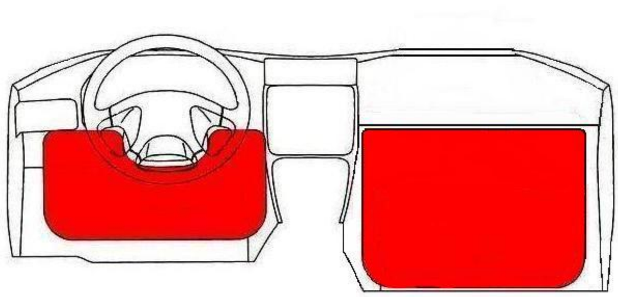


Figure 2: Driver knee airbag (DKAB) and passenger knee airbag (PKAB) application

The PKAB therefore also needs to deploy along the instrument panel (glove compartment) and the lower extremities in the same way as explained for the driver's side, but at a higher deployment distance. The aim of this study is to develop a PKAB design making use of advanced driver airbag simulation methodology. The new corpuscular method (CPM) applied in parallel to the control volume method (CVM) focuses on the following topics:

- Validation of the DKAB model to dynamic impactor tests
- Investigation of the unfolding characteristics of the numerical DKAB model
- Prediction of the PKAB energy absorption potential and unfolding characteristics

The numerical PKAB model results are finally verified by dynamic impactor tests. The advanced airbag simulation method was developed to cover the challenging OoP load case in the late 1990s. This advanced method is applied here and discussed in terms of knee airbag design. The limits and possibilities of the numerical design of airbags in general can be found in literature, for example [1], [2] and [3].

2 Knee airbag model

The model of the frontal DKAB with a volume of 17 L was set up for initial evaluation. The fabric cushion properties were implemented using the orthotropic fabric material model of LS-Dyna. The cushion fabric has been silicon-coated, therefore the total leakage includes the gas loss near the inflator area only. The real hole, through which the inflator pipe is connected with the wire harness, was modelled with one ventilation hole. The gas outflow through the seams was not covered within the numerical model. The airbag cover housing was not included in the study. The CVM inflator model was first validated to real tank test results (pressure response) and further compared to the CPM pressure time history. The inflator gas mass flow and temperature curve were derived using an empirical thermodynamic approach. The constant composition of the inflator gas was supplied by the gas generator manufacturer. The gas mixture consists of six different gas fractions and 150,000 particles are used to represent the mixed fluid. Pressure is initially defined inside and outside the airbag atmosphere. Both airbag cushions are modelled with approximately 11,500 nodes and 23,000 elements at an average element size of 7 mm. All of the simulations are performed with LS-DYNA Version 971 R3 11703 MPP on a Linux cluster with 4 CPUs. For more detailed information on the corpuscular method, please refer to [4].

2.1 DKAB and PKAB cushion geometry

As explained above, the PKAB model needs to deploy at a higher distance to cover the passenger occupant's lower extremities effectively. The sketch in Figure 3 below shows the PKAB cushion design compared to the initial DKAB cushion design.

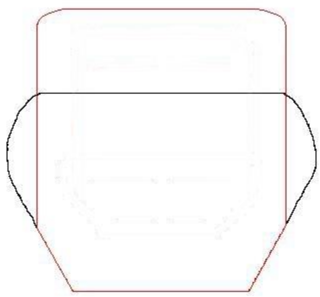


Figure 3: Driver knee airbag and passenger knee airbag reference geometry

To limit the volume increase, the PKAB geometry is higher but the width is smaller compared to the DKAB cushion. Additional tethers restrict the thickness of the blown-up bag. The volume of the PKAB cushion is approximately 20 L.

2.2 Gas in- and outflow implementation

Figure 4 depicts the real DKAB module folded into the container emphasising the lateral inflator bottle location.

Figure 4: Emphasised cylindrical inflator location in the real DKAB module with container

The gas flows into the folded cushion at the top end of the inflator bottle. At this location, the gas inflow was modelled for the CPM airbag models. The gas loss during inflation takes place at the hole where the inflator bottle is plugged into the folded cushion. Within the simulation, the airbag is modelled as a closed volume with ventilation hole, whereas in reality the volume is open at the inflator bottle plug-in location. The FE elements indicating the ventilation (outflow) hole are positioned close to the outflow location in the real airbag module shown in Figure 5 for the CVM DKAB and PKAB models.

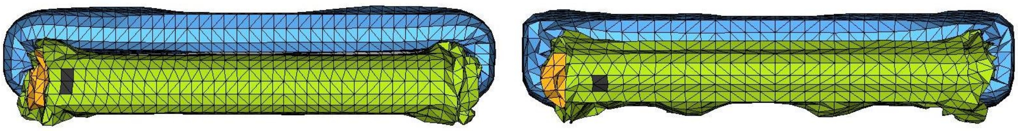


Figure 5: DKAB vent hole size (left) indicating the energy loss (gas outflow) for the PKAB derivation (right)

The gas (energy) loss at the inflator area was modelled for the PKAB model in the same way as for the DKAB model (lower cushion geometry corresponds in both airbag types, see also Figure 3). The basic idea is that at approximately the same volume, the derived PKAB will have approximately the same pressure level and consequently more or less the same gas loss at the inflator region. For the CPM simulation, the inflator location was modelled according to the CVM simulation result. The ventilation hole outflow area was not scaled, but modelled with FE elements (see Figure 6 for the DKAB).

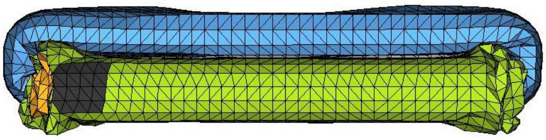
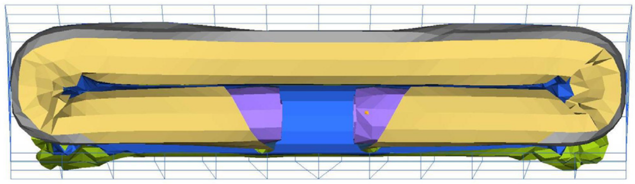


Figure 6: DKAB vent hole modelling for CPM simulation

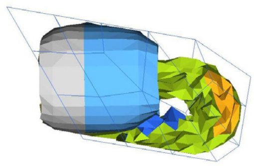
Because the outflow area was approximated with FE elements, the FAC factor here is equal to 1.0. The inflator bottle was not modelled within this study, since its volume was considered to be small compared to the airbag volume deployed.

2.3 Folding of the airbag

The two-dimensional flat airbag cushion was folded according to the real folding pattern using commercial folding software. The folded cushion was compressed into the container by relaxing the folded FE mesh. Figure 7 depicts the mesh of the folded DKAB after relaxation in the front and side view.



Front view



Side view

Figure 7: Folded PKAB FE package model (relaxed FE mesh) – front and side view

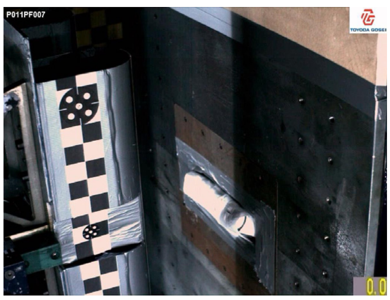
The derived PKAB cushion was folded according to the DKAB folding scheme and compressed into the container according to the same pre-simulation method.

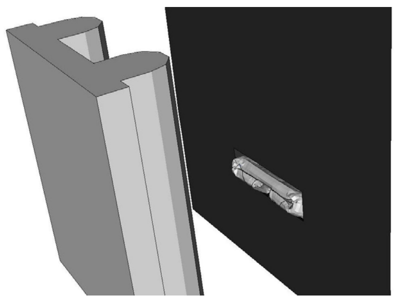
2.4 Experimental validation

A number of experimental tests were carried out for the purpose of validating the DKAB module ranging from inflator tank tests and dynamic impactor tests:

1. Gas generator tank test
2. Folded DKAB inflation dynamic impactor test at impactor mass 1 (m1) and mass 2 (m2)

The gas generator was fired inside a tank and the pressure measured. Dynamic impactor tests were carried out using a linear test rig at similar velocity. The impactor was shaped as a combined knee-tibia surface (see Figure 8) and its mass (m1 < m2) corresponds to the hybrid 50% dummy in different crash scenarios. The distance from the impactor top edge to the mounting plate at gas generator ignition was 300 mm. Impactor acceleration was measured at two locations near the impactor centre of gravity (average values are further used in this paper).





(a) Test set-up (b) Simulation model

Figure 8: Combined knee-tibia impactor test set-up and simulation model

In the simulation model, the impactor and the mounting plate (baffle) were modelled as rigid surfaces (rigid body in case of moving impactor). To confirm the predicted numerical performance of the PKAB, further dynamic impactor tests were carried out finally:

3. Folded PKAB inflation dynamic impactor test at two mass levels

3 Simulation results

Within this section, the simulation results are presented starting with the inflator tank test validation followed by the DKAB airbag dynamic impactor test validation. Then the simulation results of the PKAB performance prediction are presented.

3.1 Inflator tank test

The diagram in Figure 9 depicts the tank test pressure response versus the simulation time history of the CVM and CPM.

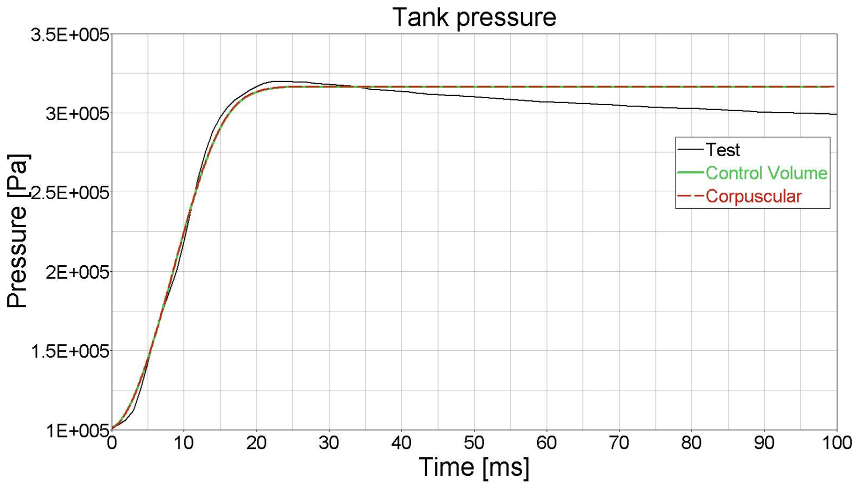
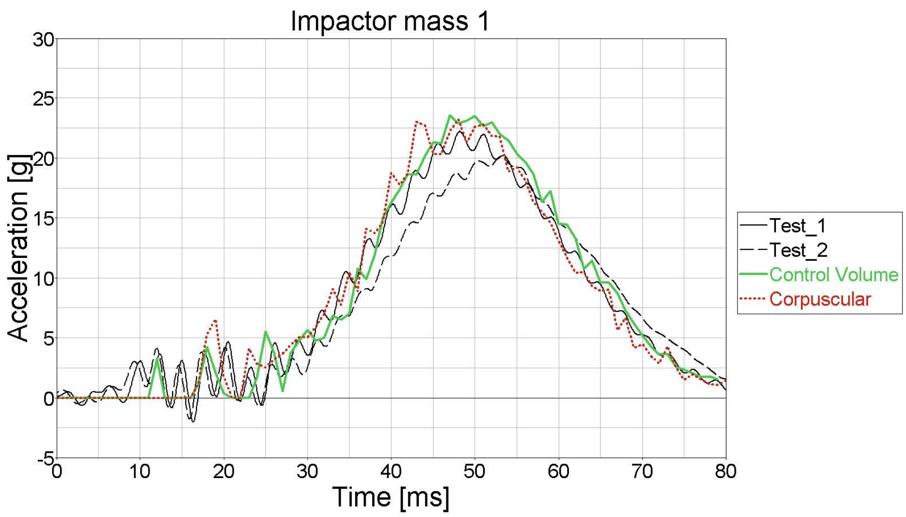


Figure 9: Tank pressure time history, CVM versus CPM result

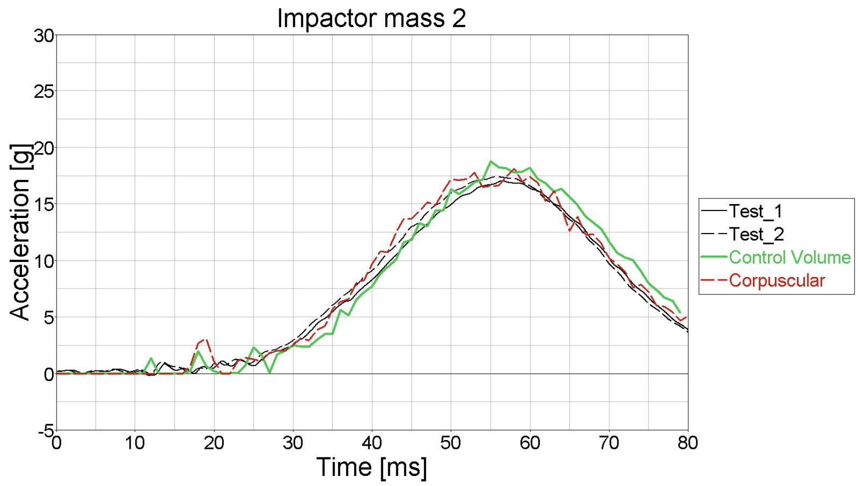
Because the heat loss at the tank walls occurring in the real tank test is not covered by the adiabatic simulation, the pressure time history starts to differ from the tank pressure response at approximately 30 ms. The inflator mass flow was empirically derived based on the tank test pressure response at a constant inlet temperature in time.

3.2 Driver knee airbag (DKAB) validation

Figure 10 below plots the acceleration validation of the dynamic impactor test of the DKAB airbag model for the different test scenarios (impactors m1 and m2).



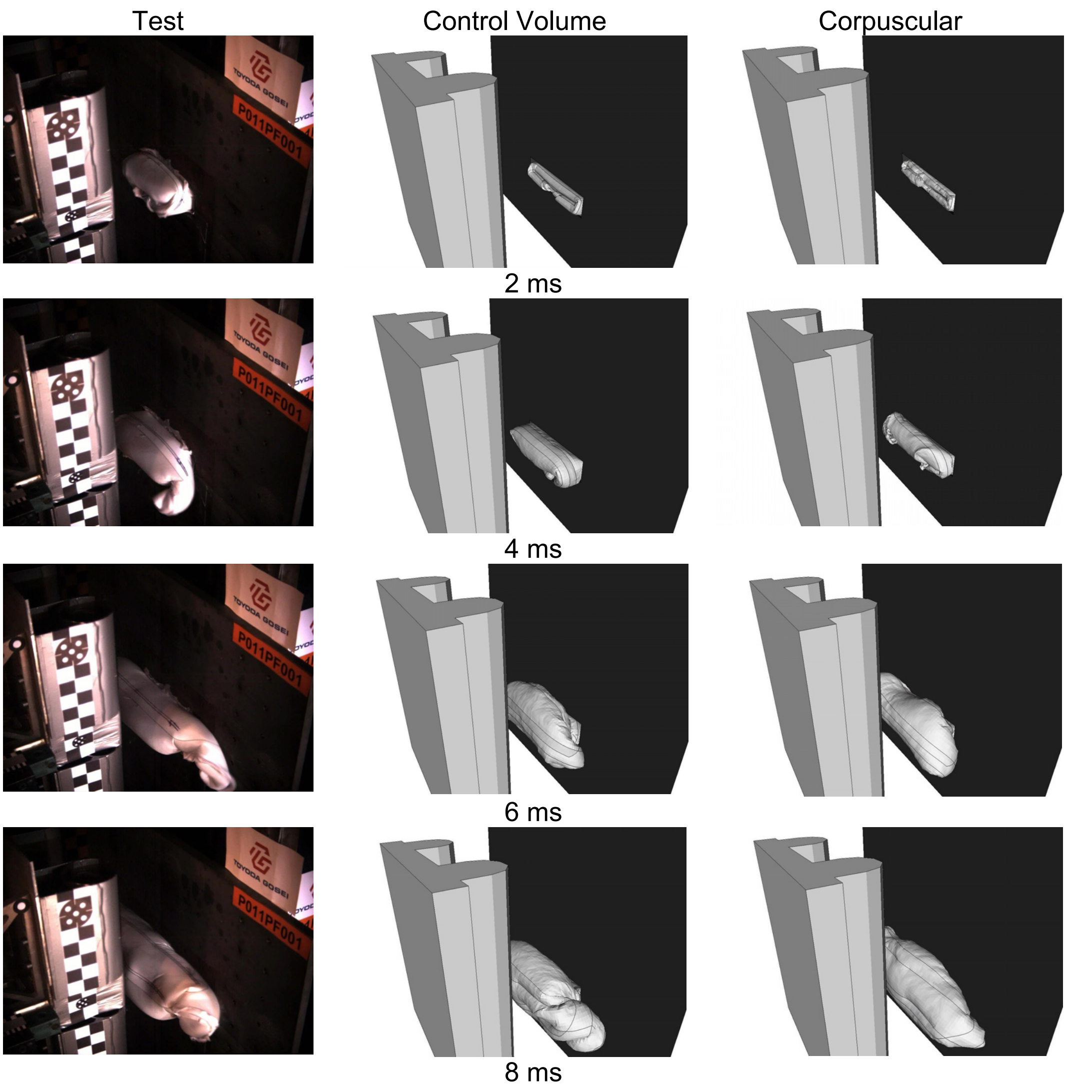
(a) Impactor m1



(b) Impactor m2

Figure 10: DKAB dynamic impactor acceleration validation – impactors m1 and m2

Deployment plots for the initial 16 ms (in 2 ms steps) of early airbag inflation are presented in Figure 11 for comparing the test response with the CVM and CPM simulation time history (impactor m1 scenario in iso view).



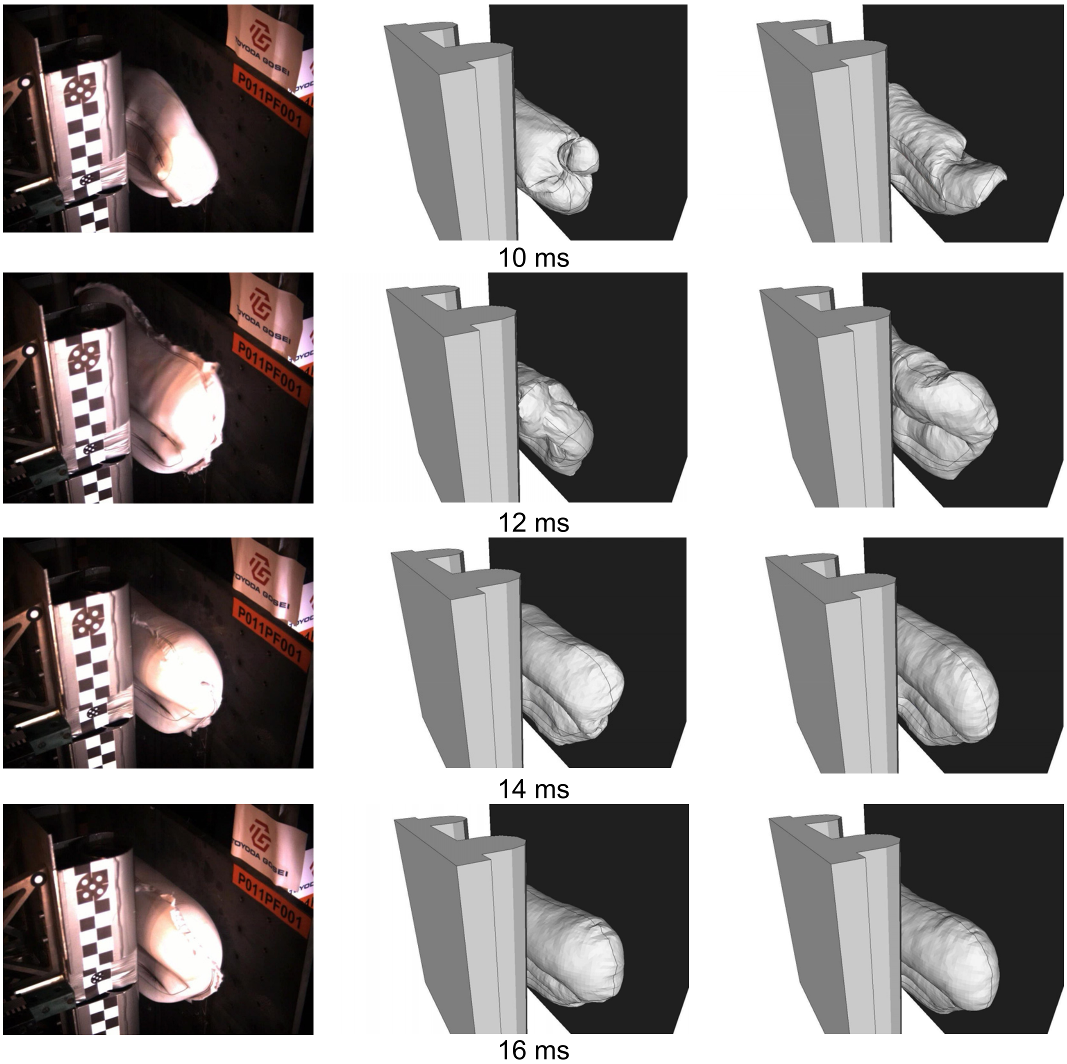
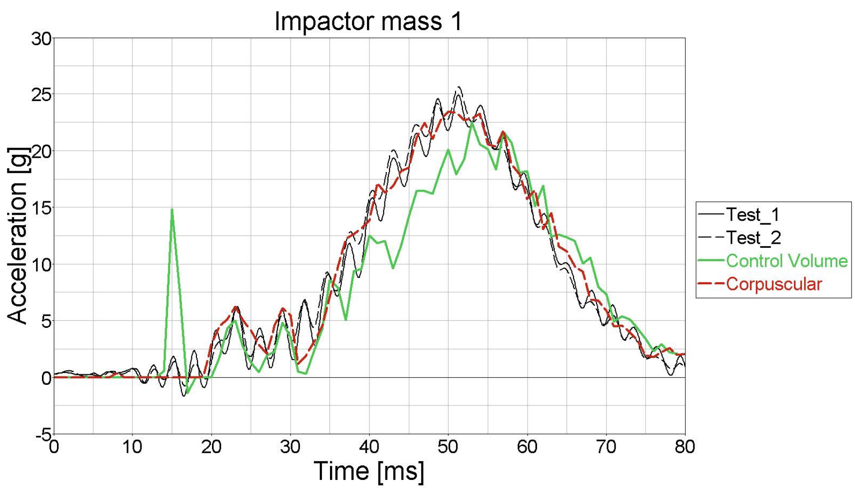


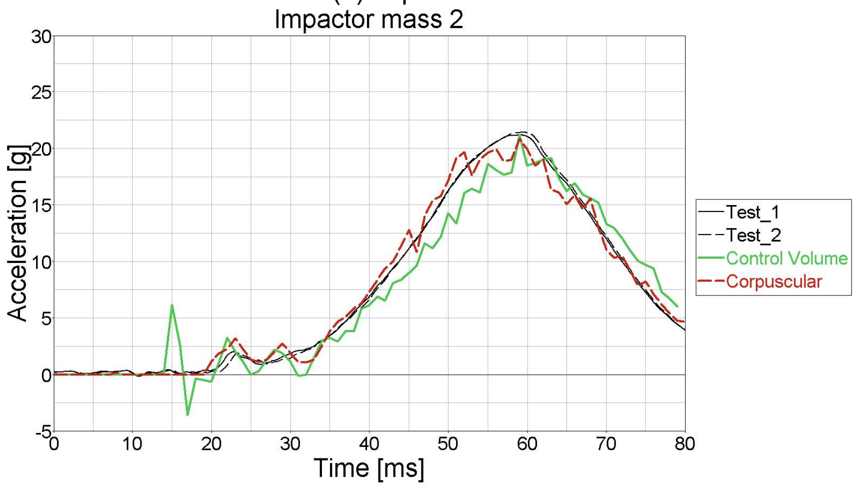
Figure 11: DKAB early inflation animation test versus CVM and CPM time history – m1 impactor

3.3 Passenger knee airbag (PKAB) performance prediction

The predicted PKAB performance results are directly compared with the confirmation test results here. First the impactor acceleration at both mass scenarios comparing the simulation time history with the test response.



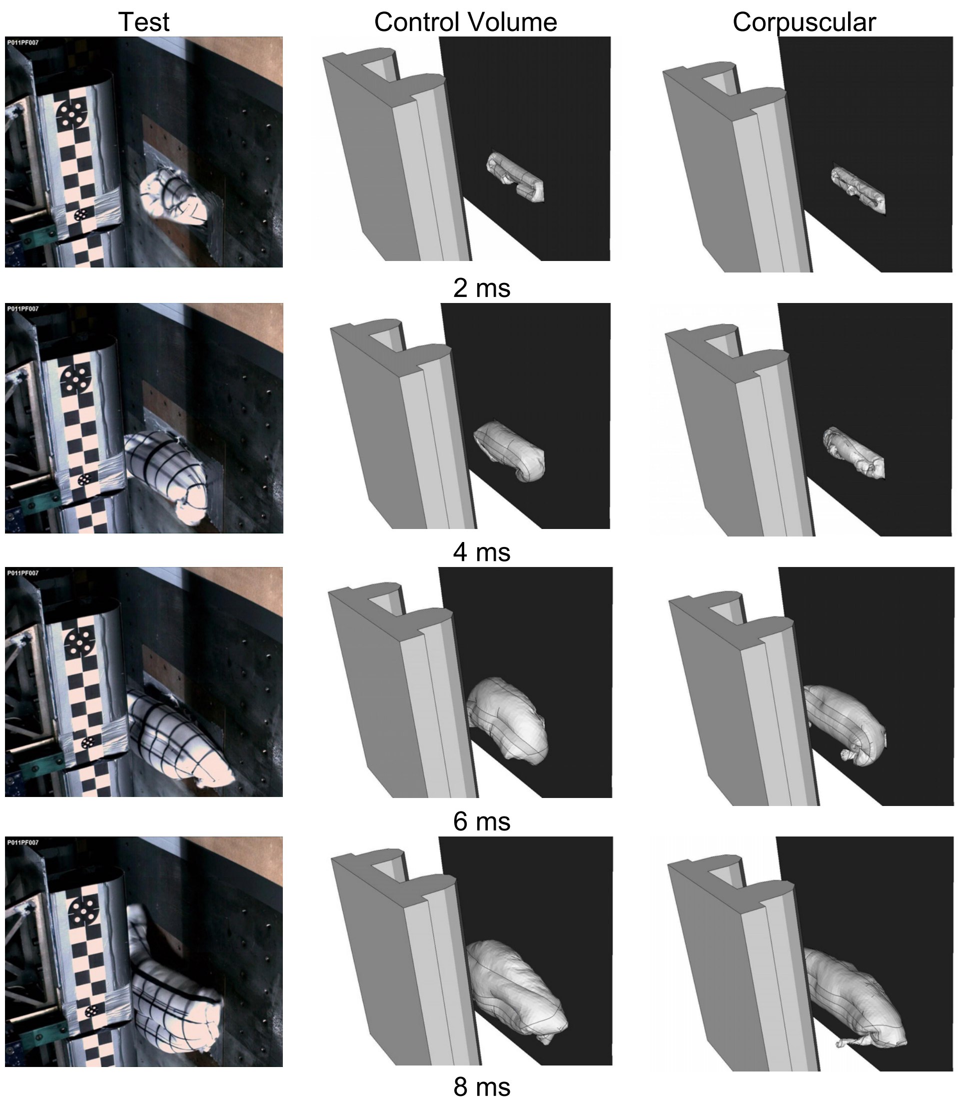
(a) Impactor m1



(b) Impactor m2

Figure 12: PKAB dynamic impactor acceleration prediction

Figure 12 below presents the early inflation characteristics of the PKAB for the first 16 ms in 2 ms steps again in iso view (impactor m1 scenario).



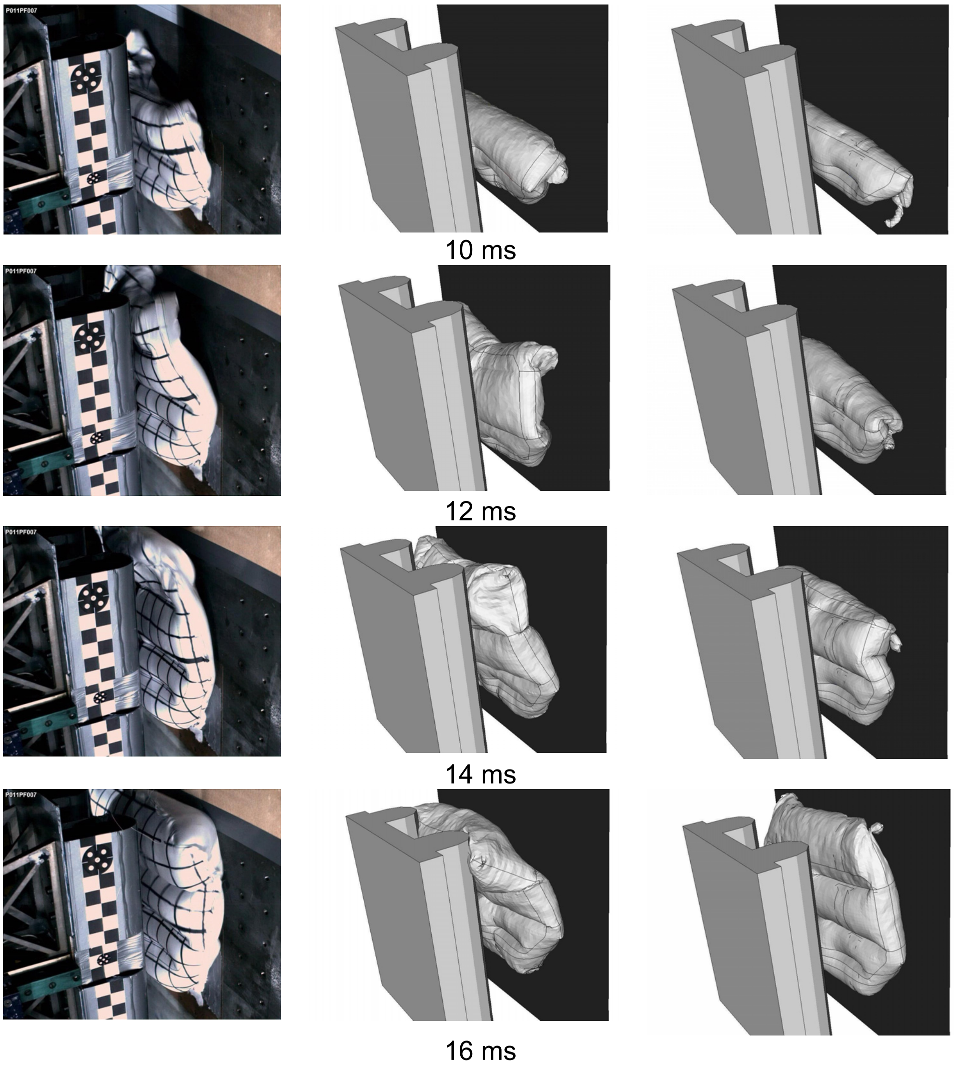


Figure 13: PKAB early inflation animation test versus CVM and CPM time history – m1 impactor

4 Discussion

Before the predicted PKAB simulation results are discussed, the validation results of the DKAB are analysed within this section.

4.1 DKAB validation

The CVM and CPM DKAB acceleration validation shows good correlation of both test scenarios (see Figure 10). Implementing the ventilation hole area from the CVM model, the effective area is decreased due to the fluid flow outflow effect at an orifice for the CPM simulation as explained in Figure 14 below.

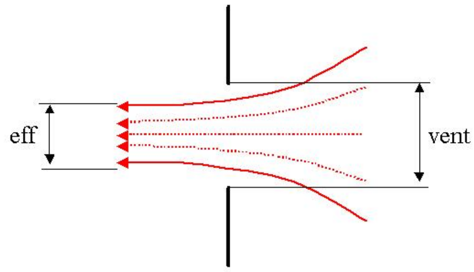


Figure 14: Effective outflow area decrease through an orifice indicated by streamlines

CPM acceleration DKAB model validation was reached by increasing the ventilation hole outflow area by 80% to match the DKAB test response and the CVM simulation result level. The impactor acceleration time history reached by the CPM with the ventilation hole area corresponding to the CVM model outflow compared to the impactor test response is shown in Figure 15 below.

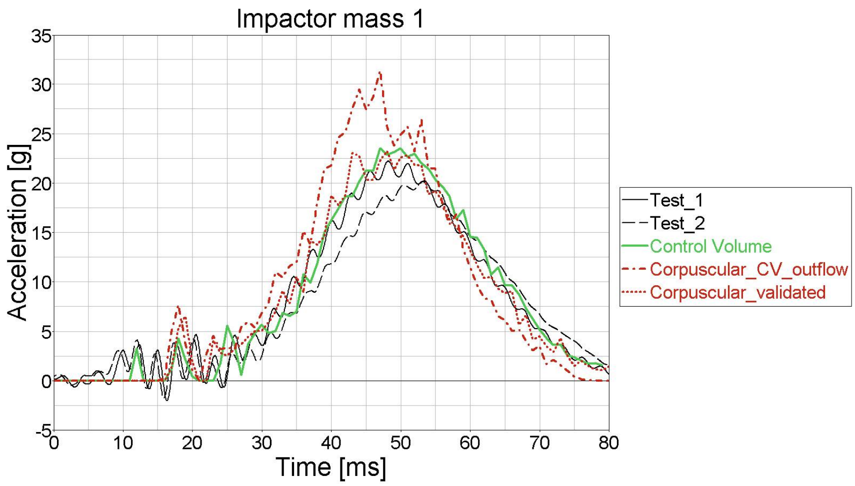


Figure 15: DKAB CPM outflow effect for the impactor (m1) test acceleration time history

Lower gas outflow through a smaller hole leads to a lower energy loss and therefore to a higher acceleration time history. Figure 16 plots the outflow areas implemented into the DKAB airbag CPM models with FE element surfaces after validation (left) and the initial model with the outflow area corresponding to the CVM airbag model (right).

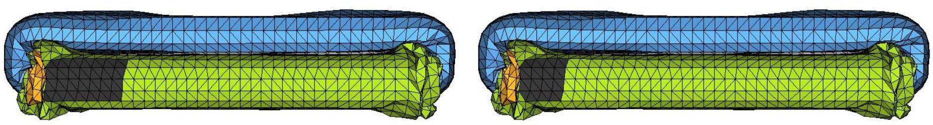
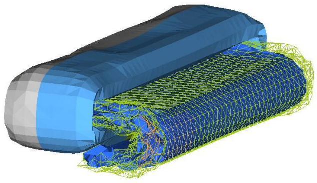
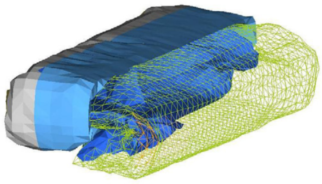


Figure 16: DKAB CPM validated outflow area (left) versus ventilation hole area size derived from CVM validation (right)

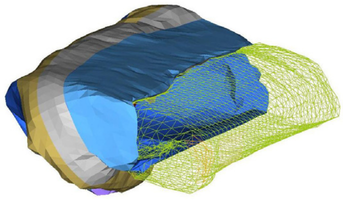
When the simulated unfolding characteristics are compared to the test response, the general inflation mode is similar as can be seen in Figure 11. First a lateral deployment takes place, followed by an upward deployment along the mounting plate (baffle). However there are also some differences. The initial deployment (< 4 ms) differs from the test response for both simulation methods. This could be explained as follows for the CPM simulation: because the cylindrical inflator was not taken into account in simulation (see Figure 7 side view and Figure 4), the initial inflowing gas is not able to pull the DKAB folded package out of the container as presented in the following Figure 17.



0 ms



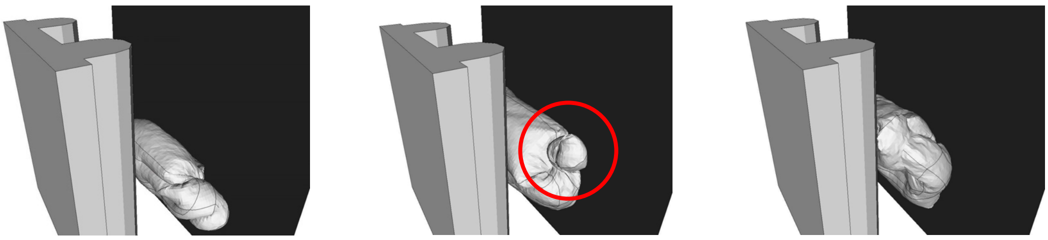
2 ms



4 ms

Figure 17: Initial gas flow into the folded package – DKAB model

In the control volume simulation, the internal cushion volume is pressurised uniformly. Therefore the folded layers block initially. This effect supports the prevention of the initial push-out of the folded package out of the container. Evaluating the test animation response in Figure 11 for early airbag inflation (2 to 4 ms) indicates that the folded package is indeed pushed out of the container by the inflowing fluid. After the folded cushion is pushed out, the lateral deployment is more distinctive from 4 to 8 ms as the inflation in the upward direction along the mounting plate starts in the test and both simulation methods at 8 to 10 ms. Looking into the simulated unfolding mode in more detail, the CPM is reasonably able to reproduce the lateral unfolding, whereas the CVM inflation shows non-realistic twisting (see Figure 18 below).



8 ms 10 ms 12 ms

Figure 18: DKAB cushion twisting observed during CVM unfolding

This can be handled by the contact algorithm and leads to full deployment at 14 ms. Both simulation methods show a good correlation of the simulation time history to the test response in terms of full deployment timing.

4.2 PKAB prediction

The outflow area was implemented for the PKAB model according to the DKAB method to predict its mechanical performance first with the CVM and then with the CPM simulation. The result shows that the CVM acceleration time history underestimates the impactor acceleration measured in the confirmation test, whereas the CPM simulation can predict the test response for both impactor scenarios very well (see Figure 12).

When the simulated unfolding characteristics are compared for both airbag designs, the general inflation mode (lateral and upwards) is similar for both cushion types as can be seen in Figure 11 and Figure 13. There are similarities especially when comparing the very early deployment of both airbag models to the test response for the first 6 ms due to the same design of the lower part of the cushion in both airbag types. But there are also some differences in the unfolding mode of both airbag types. Because the PKAB is higher and not as wide, upward inflation is more distinctive and the gas is transported to a longer upward distance. Looking again into the unfolding mode in more detail for the PKAB, upward deployment starts again at 8 to 10 ms. Although the cushion volume is pressurised uniformly, the CVM can reproduce the unfolding scheme, whereas the CPM displays some twisting highlighted in Figure 19 below.

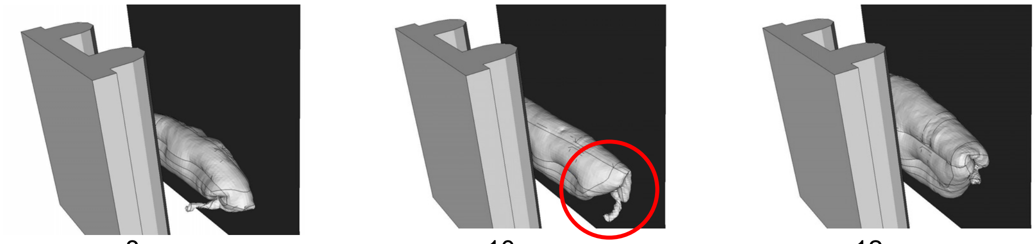


Figure 19: PKAB cushion twisting observed during CPM unfolding

The twisting effect stays until the gas travels through the additional third tether and full deployment takes place at 16 ms. Therefore the gas transported through the elongated PKAB cushion is reproduced slightly differently by the CPM simulation, which also displays a delay of 2 ms to the CVM time history. Comparing the test response for both airbag types, the PKAB cushion is fully deployed at 16 ms – 2 ms delayed to the DKAB.

5 Conclusion

The airbag simulation method presented with the fluid modelled as particles predicts the mechanical performance of the PKAB. Slight differences occur in the prediction of the real PKAB cushion early inflation mode with the advanced real fluid flow simulation method. The control volume PKAB prediction underestimates the mechanical performance, but can reasonably predict the unfolding characteristics. This indicates that the energy loss during the more complex PKAB dynamic unfolding process plays a significant role, since this result is not obtained for the DKAB simulation with its different design (lower height) and therefore a lower folded package density.

To further investigate the physical problem of early inflation of a complex knee airbag with its effect on the airbag's mechanical performance, the following parameters could have a significant impact on the numerical simulation result:

- Introduction of the cylindrical inflator to discretise the real fluid inflow condition
- Modelling of the lateral outflow hole according to the hardware module
- Inserting gas leakage of the seams
- Study of non-folded cushion deployment in order to study the cushion friction effect in the folds
- Characterisation of main inflator parameters changing in time (temperature, mixture)

The knee airbag simulation results presented in this paper help thanks to stepwise placement of the inflator bottle, reconstruction of the ventilation hole and the gas leakage through the seams to better understand the physical dynamics of early inflation problems, e.g. the additional seam gas leakage would reduce the effective outflow area at the inflator and therefore an impact on the unfolding kinematics could be expected. With a more detailed description of the inflator supplied gas temperature changing in time at the inlet location, which replaces the empirical derived mass flow and constant temperature approach applied in this study, an additional improvement of the physical airbag system model could ultimately be reached.

6 References

[1] Beesten, Hagen, Rabe: "Out of Postion Simulation – Possibilities and Limitations with Conventional Methods", Airbag 2002, Karlsruhe, Germany.

[2] Beesten, Hirth, Reilink, Remesperger, Rieger, Seer: "OoP-Simulation, A Tool to Design Airbags? Current Capabilities in Numerical Simulation", Airbag 2004, Karlsruhe, Germany.

[3] Hirth, Haufe, Orlovsson: ”Airbag Simulation with LS-Dyna Past – Present - Future”. 6th European Users’ Conference 2007, Gothenburg, Sweden.

[4] Lars Olovsson, Impetus Advanced finite element analyses: “Corpuscular method for airbag deployment simulations in LS-DYNA”, 2007, Impetus Afea AB, Huddinge, Sweden.

[5] “LS-DYNA Keyword Users’ Manual Version 971”, Livermore Software Technology Corporation (LSTC), Livermore, USA, May 2007.