MATHEMATICAL MODELLING OF THE EARLY PHASE DEPLOYMENT OF A PASSENGER AIRBAG – FOLDING USING ORIGAMI THEORY AND INFLATION USING LS-DYNA PARTICLE METHOD

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ABSTRACT

Initial evaluation of the particle method for mathematical out-of-position simulations was performed. The evaluation was carried out by means of static inflation and impactor tests. In the out-of-position load case, the occupant is initially positioned very close to airbag module and the interaction airbag-occupant occurs during the early deployment phase of the airbag. Thus a realistic representation of the folding pattern together with an explicit modelling of the gas flow and the non-uniform pressure distribution play an important role. The first folding step of a 3D passenger airbag concerns the flattening to a 2D shape. The method used in this study was based on mathematical origami theory. The method consists of an initial user specification of one or a few main constraint folds. The remaining creases, which are needed to flatten the 3D airbag to a 2D state with a minimum area loss, were generated using the origami theory. The actual flattening was performed by solving a nonlinear optimization problem. The subsequent folding of the flat 2D airbag into a housing module was carried out by commercially available software. In the mechanical impactor tests, the airbag was inflated with chest and head shaped impactors resting on top of the airbag. The tests were modelled using the particle method for the gas flow and the predictions from the models were compared to the results from the mechanical tests. Good agreement between predictions and test results were obtained. Next step will be to evaluate the method by means of airbag inflation with an occupant positioned close to the airbag.

KEYWORDS:

3D passenger airbag, Particle method, Origami folding, Out-of-position

INTRODUCTION

The frontal passenger side airbag is a widely used occupant protection system which significantly reduces the number of injured occupants involved in passenger vehicle accidents. The passenger side airbag is particularly effective in reducing the risk of injury for unbelted occupants (IIHS 1996, NHTSA 1996). For occupants in a normal seating position, the passenger side airbags offer good protection. For occupants close to the airbag at the time of airbag deployment (out-of-position situations), the protective effect of the airbag is more limited and has also been the cause of casualties. Some reasons for these causalities are that the passenger side airbags usually have a large volume (often 150 litres) and inflate towards the occupant. The front of the bag approaches the occupant at a very high velocity. In one study the front of a driver side airbag was found to approach the occupant at a velocity of 256 km/h (71 m/s) (Smock et al. 1995). In another study the bag front velocity was found, in film analysis, to range from 160 km/h to over 320 km/h (Kossar et al. 1992). Due to these severe circumstances, there is a need for a frontal passenger airbag system that minimizes the risk of injury for out-of-position occupants and at the same time provides effective protection for the in-position occupants.

Developing such a system can be made in an efficient way by the use of mathematical modelling. However, despite the fact that the automotive industry has been using numerical simulations for occupant safety for many years, predictive modelling of airbag deployments is still a highly challenging task. For predictive modelling of airbag deployment several key ingredients are required: a realistic folding of the airbag and modelling of the fluid dynamics (gas) including the interaction between the fluid and the structure.

In out-of-position simulations, study of the early stage of airbag inflation is of interest and the simulation model must consequently show a high level of accuracy during the initial unfolding of the airbag. The airbag is folded according to a fold pattern to fit inside the housing and the chosen pattern has a significant influence on the deployment of the airbag. Folding of the mathematical airbag model can be a complex task, especially for a three dimensional airbag. A passenger airbag is usually sewn together from three or more flat parts, which give the assembled airbag a complex 3D shape. Folds must be introduced when laying the airbag flat. The number of folds, their size and their location depend on how the airbag is laid flat before folding. Furthermore, many wrinkles appear when a passenger airbag is laid flat. Taking all wrinkles into consideration would be unreasonable in a model due to the difficulty of predicting their location and the large number of elements which would be required to model them. However, the influence of the wrinkles may be of minor importance as long as the correct fabric area is used in the model.

A method for modelling 3D airbags was developed by Eriksson and Fältström (1998). In this method, a flat foldable mesh was created based on measurements on the physical airbag in a flat configuration. The flat airbag mainly consists of four flat surfaces that were reproduced with some modifications in the model. The flat model was folded using standard features in pre-processors. Due to the simplifications made when creating the flat mesh and due to the distortion of elements when folding, the shape of the folded bag differs compared to the physical airbag.

Once a folded airbag model is obtained, the inflation of the airbag needs to be included in the model. Modelling of the inflation of a folded airbag can involve a deterministic analysis (control volume) of the gas flow into the airbag or the gas flow can be discretised in space. In the control volume analysis the action of the gas is simulated by solving the associated thermodynamic equations of the enclosed mass of the gas, i.e. the gas volume is not discretised in space. Gas inflow, leakage and orifice outflow are treated approximately and the effects of gas jet and delayed gas flow through pocket formation inside folded airbags is treated empirically to achieve engineering solutions of good practical quality.

In LS-Dyna, the discretization of the gas can be modelled by either a continuum based coupled fluid-structure method (ALE) or a particle method. In the ALE method, the gas is discretised in space using an eulerian approach and the bag as a deforming lagrangian structure. The eulerian and lagrangian meshes are coupled through a direct or penalty method. In the particle method, the discretization of the gas is made by several hundred thousands of small particles. The particles have contact with each other as well as the surrounding lagrangian structure. Both the control volume method, which is computationally very efficient, and the coupled fluid-structure method have been used previously to evaluate the airbag occupant interaction in the early phases of inflation. The particle method has an advantage of being less time consuming than the ALE approach, while the discretization of the gas is still considered.

There have been some analyses carried out in modelling the occupant airbag interaction during the inflation of the airbag. The deterministic modelling approach for out-of-position simulations was evaluated by Fredriksson (1996), where it was found that the chest acceleration of a HIII dummy was too large when using a jet model. It was concluded that the model can not predict the occurrence of large vortices, i.e. in the jetting model the gas is not forced out to the side of the airbag after striking the obstacle present, and thereby causing non-physical aggressiveness. The influence of different folding patterns on the out-of-position performance of the airbag was evaluated by Mao et al. (2001). A strong influence of folding pattern on the out-of-position injury potential was found and especially the conventional accordion folding scheme was found to substantially higher injury potential than the other folding schemes. This study however, was carried out using the control volume approach for the gas analysis.

The objective with this study was to perform an initial evaluation of the applicability of mathematical modelling of the out-of-position load cases by using realistic representation of the airbag folding pattern based on origami theory together with inflation using the particle method. Minor comparisons to the control volume method were also carried out.

METHOD

A mathematical model of a frontal three-dimensional (3D) passenger side airbag was created by beginning with the folding. The first folding step of the airbag concerned the flattening to a 2D shape, which was carried out by a new method based on mathematical origami theory. The subsequent folding of the flat 2D airbag into a housing module was carried out by commercially available software. The final folded airbag was inflated using the particle method in various load cases and the results compared to corresponding mechanical test results.

MATHEMATICAL AIRBAG MODEL

A mathematical model of a frontal three-dimensional passenger side airbag with a volume of 126 L (at the pressure 0.1 bar) was created for the evaluations. The airbag was supplied with two ventilation holes with a diameter of 65 mm. The fabric thickness was 0.34 mm and the airbag was coated with a silicone liner to prevent gas from leaking out. The fabric material model in LS-DYNA was used to simulate the material behaviour of the airbag fabric. An isotropic description of the airbag fabric was considered to be sufficient for the purposes of this study. The mathematical model used for folding was based on three dimensional CAD data of the airbag shape. A realistic flattening to a 2D state was performed by using the origami method developed by Cromvik (2003, 2007). The remaining folds together with a compression simulation were carried out with the aim of fitting the airbag into the housing module. The flat 2D state of the airbag was used for the reference geometry. The house cover was not included in the study.

The total leakage in a passenger airbag includes the gas loss around the inflator and at fabric attachment in the housing, through the fabric (especially if not coated) and at the seams, which also separate to a certain degree when the pressure increase. In the model, a simplified approach was used where all leakage sources were lumped to a non-pressure dependent leakage area, positioned in the housing area of the airbag fabric. The particle gas generator model was validated by means of a tank test and also compared to the results from a corresponding control volume model. The gas composition, mass flow and temperature together with the corresponding tank test pressure for the gas generator model validation were supplied by the manufacturer of the gas generator.

Mainly the particle method was used for the airbag inflations. The airbag pressures for the particle model were measured at the same locations as for the mechanical tests, but using a larger area than the small gauge area. A few comparisons were also made to the control volume method, which is based on uniform pressure assumptions. In these cases, no jetting was used for the control volume model. The final airbag model consisted of 18000 deformable shell elements and the analyses were carried out using LS-Dyna SMP version 971_10286 with 450000 particles.

FOLDING USING MATHEMATICAL ORIGAMI THEORY

A frontal passenger side airbag is usually sewn together from three or more flat parts, which gives the assembled airbag a complex three-dimensional shape. When the bag is laid flat, larger folds (creases) and smaller wrinkles are introduced. The method used in this study to generate the crease pattern in the mathematical model was based on numerical origami theory (Cromvik, 2003, 2007). The current algorithm is capable of creating the crease pattern for symmetric quasi-cylinders, i.e. for a perpendicular cut-off cylinder with an arbitrary polygonal cross-section. In the method, the cylindrical shaped 3D airbag is thus initially approximated by a polyhedron, Figure 1. The complexity of the crease pattern increases with the number of vertices in the polyhedron discretization. The lower airbag part which encloses the gas generator is not included in the flattening.

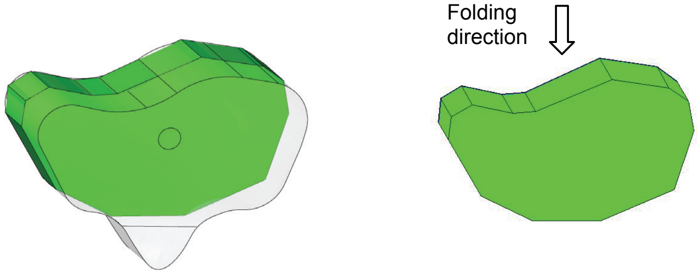


Figure 1. Approximation of a cylindrical shaped 3D airbag by a polyhedron.

The polyhedron, which was created from the 3D airbag, is split by one or a few user-required main folds. These main constraint folds correspond to the folds forced by the mechanical folding machine and will be forced to be part of the final crease pattern. The constraint folds divide the airbag polyhedron into several smaller sub-polyhedrons. Figure 2 shows two different types of forced constraint folds (thick lines), which will result in different layout of the final crease pattern (thin lines). For each sub-polyhedron, the remaining creases which are necessary to flatten the airbag to a 2D state are generated using mathematical origami theory. The final generated crease pattern, which is marked by thin lines in Figure 2, can be shown to be sufficient for folding the airbag flat.

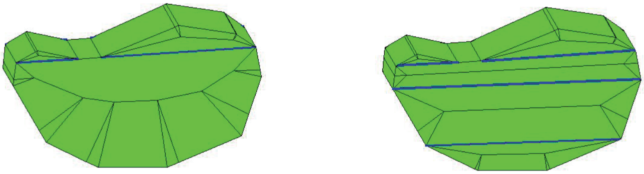


Figure 2. Main constraint folds (thick lines) and creases generated with origami theory (thin lines).

The polyhedron is now provided with a complete crease pattern. The actual folding of the polyhedron to a flat two-dimensional state is performed by solving a nonlinear optimization problem. The final crease pattern divides the sub-polygons into even smaller areas, patches. Each patch is triangulated and has a normal is associated with it. The objective function in the optimization is mainly based on the dot product of the normals of the two polygons adjacent to each fold,

$$F = \sum_{\text{crease } i} n_1^i \cdot n_2^i$$

with the constraints: no surface stretching (minimum area loss) and no surface penetrations. The upper surfaces of the final flat 2D states of the two examples are seen in Figure 3.

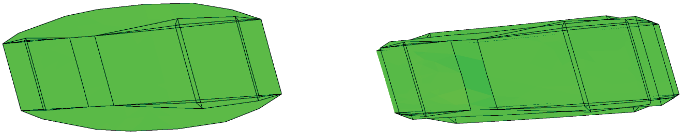
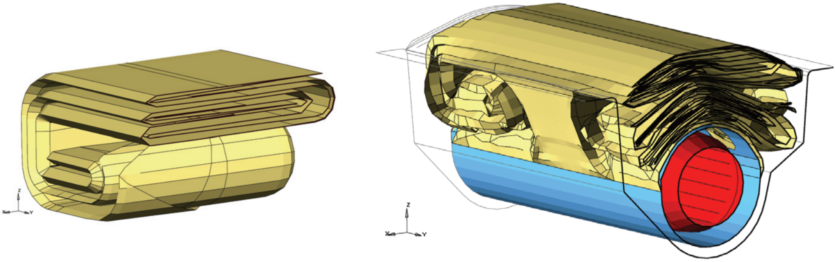


Figure 3. Final flattened two-dimensional state of the 3D passenger airbag.

FOLDING OF THE FLATTENED AIRBAG

The flattened 2D state of the airbag needed to be further folded to fit into a housing module. In this study, the flattened with one constraint fold airbag was used (Figure 3 left). This chosen crease pattern corresponded to physical airbag flattened state. The subsequent folding of the flat airbag into a housing module was carried out by the software Primer version 9.2. Figure 4 left shows the half of the folded airbag where a combined z- and roll-fold from top and bottom of the airbag was performed followed by roll-folds from both sides. The folded airbag was also compressed into housing with the aim of making space for the deflector and separating the layers of fabric material, Figure 4 right. Thus all main folds which are present in the physical airbag have been represented in the final model. The housing cover was not included in the analyses.



Folding scheme for half of the bag

Compressed airbag

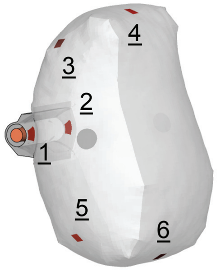
Figure 4. Final airbag model after folding and compression inside the housing module.

MECHANICAL VALIDATION TESTS

A number of mechanical tests of varying complexity were carried out for the purpose of validating the mathematical models. The complexity of the mechanical tests carried out ranged from simple tank tests to complex folded airbag tests with varying impactor masses and shapes. The following mechanical tests were carried out:

1. Tank test with gas generator (volume 146 L)
2. Unfolded airbag static inflation
3. Unfolded airbag inflation with a 22 kg rectangular chest impactor (365x700 mm)
4. Folded airbag inflation with a 22 kg rectangular chest impactor (365x700 mm)
5. Folded airbag inflation with a 8 kg hemispherical head impactor (diameter 165 mm)

The gas generator was fired inside a 146 litres tank and the pressure was measured. In the static inflation test, an unfolded airbag was inflated. The pressure was measured in the housing and at center of the mantle, both above and below the housing (Figure 5). In the mechanical tests, several pressure measurements failed and these have not been included in the results. The impactor tests were carried out in a linear impactor test rig. The chest impactor mass was chosen based on the upper body weight, including the arms, of the HIII-5%ile dummy. The head impactor mass was based on a HIII-50%ile head weight but needed to be adjusted due to test equipment limitations. The impactors were positioned to mimic the out-of-position situation. The initial distance to the airbag module was 10 mm for the chest impactor and 100 mm for the head impactor. Impactor acceleration and velocity as well as pressures in the housing were measured (Figure 5). Mantle center pressures were not measured for the folded tests. The rectangular chest and hemispherical head impactor test configurations can be seen in Figure 9 and Figure 13.



Pressure house
1. House left
2. House right

Pressure mantle center
3. Upper inner
4. Upper outer
5. Lower inner
6. Lower outer

Figure 5. Pressure measurement gauge positions.

RESULTS

GAS GENERATOR TANK TEST

In the mechanical gas generator tank test, the peak pressure 218 kPa was reached at app. 60 ms (Figure 6). The tank test was modelled using both control volume and particle methods. The pressure prediction by both models was 223 kPa, which was considered to be a minor difference compared to the test pressure. For the particle model, only the average pressure was used in the comparison and not the pressures at the specific gauge positions of the tank.

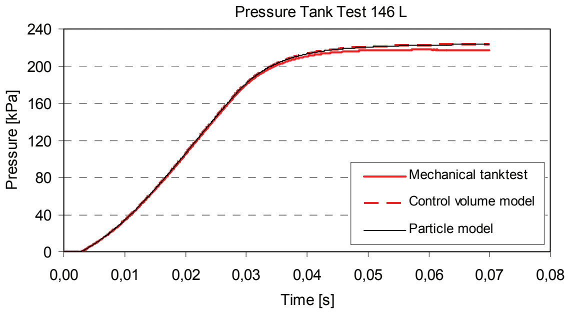
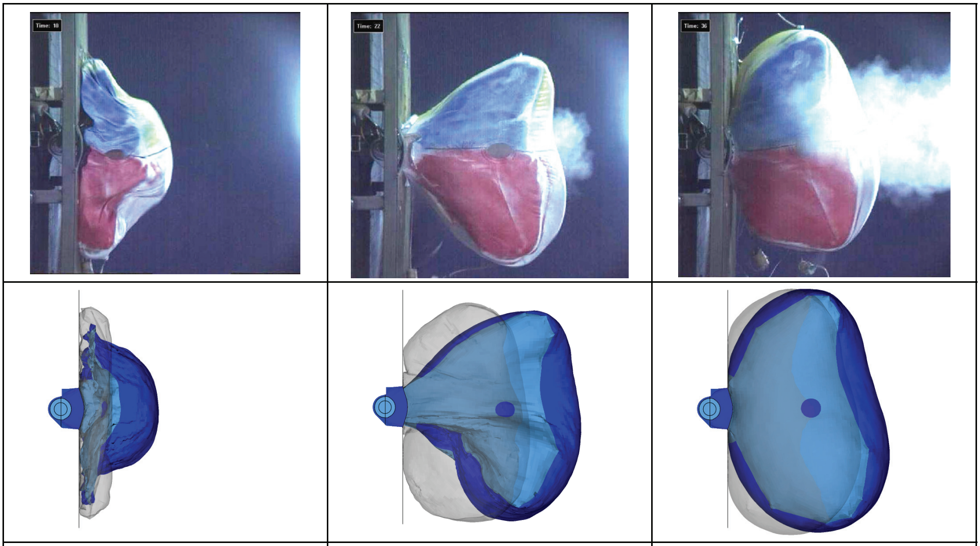


Figure 6. Mechanical tank test pressure (146 litres) of the gas generator compared to the airbag models based on the control volume and particle methods.

UNFOLDED AIRBAG STATIC INFLATION

In the static inflation test, an unfolded airbag was inflated. The mechanical test was modelled using both control volume and particle methods. Figure 7 shows the inflation of the airbag models compared to the mechanical test. The shape of the airbag model during inflation using the particle method corresponded well to the test results. Also at the rebound time of 36 ms a good correlation was obtained. Due to the uniform pressure assumptions for airbag model based on the control volume method, the inflation shape differed compared to the mechanical test and the model based on the particle method. The displacement of the model bag front based on the control volume method was app. 100 mm at 10 ms, compared to 250 mm for the model using the particle method. The bag front maximum displacement of the model was reached 6 ms later than in the test and the model based on the particle method.



10 ms – initial inflation | 22 ms – most forward position | 36 ms – rebound

Figure 7. Static inflation of unfolded airbag, mechanical test versus airbag models based on control volume (light grey) and particle method.

The pressures at the housing and at the mantle are shown in Figure 8. For all inflation load cases, the model pressures at both housing sides were reported in the figures, even if the mechanical test equivalents were not available. Only the pressure results from the airbag model based on the particle method were reported. The shape of the house pressure curve was predicted well by the model up to 30 ms, including the negative pressure values. At the mantle pressure location, a negative pressure was predicted in the model, which was not seen in the test results. The pressure test results at the mantle are from two different tests due to measurement issues. At both measurement locations, the predicted model peak pressures were lower than the test peak pressures. For the particle model, large variation of the pressure between the right and left side of the housing was observed, which was not seen in the test results. Also, in the tests, higher peak pressure was reached in the mantle than in the housing, which was not observed in the model results.

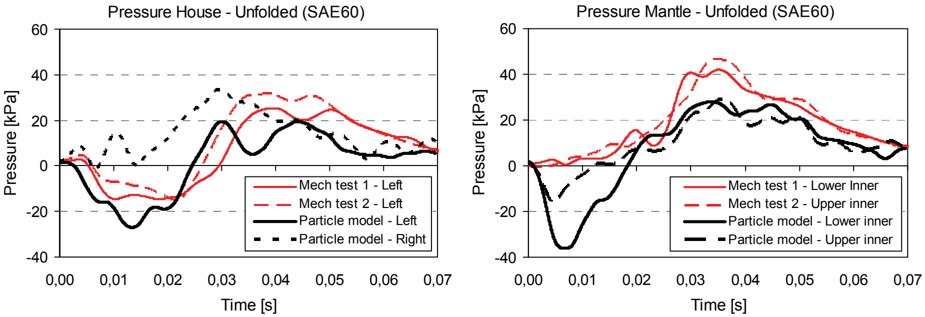
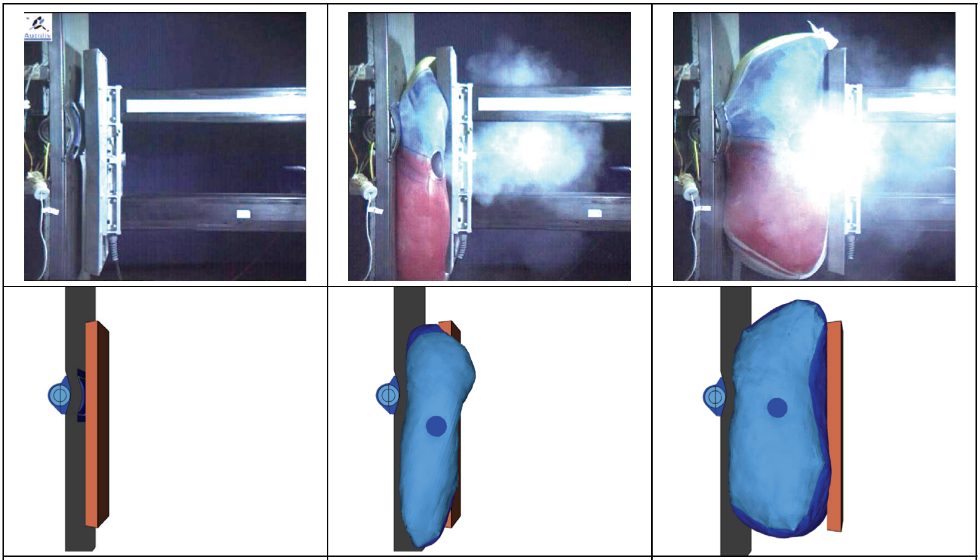


Figure 8. Static inflation of unfolded airbag, pressure in housing and at mantle.

UNFOLDED AND FOLDED AIRBAG INFLATION WITH CHEST IMPACTOR

The inflation of the folded airbag model using the particle method has been compared to the mechanical test in Figure 9. The airbag model inflated more uneven compared to the test, which is seen at time 20 ms. Also, a small inflation delay in the time frame up to 14 ms was observed for the model compared to the test. For the remaining inflation, the model corresponded well to the test and the model contact area to the impactor was well represented. The inflation of the unfolded model has not been shown.



0 ms – initial position | 20 ms – impactor covered | 38 ms – max impactor velocity

Figure 9. Folded airbag with chest impactor, mechanical test versus airbag particle model.

For the unfolded load case, too high pressures were predicted by the model up to 17 ms (Figure 10). The model pressures at the two house measurement locations varied at the time of the test peak pressure. The test pressure result was in between the two model pressure results. For the folded load case, the pressure peaks and shape were well predicted by the model.

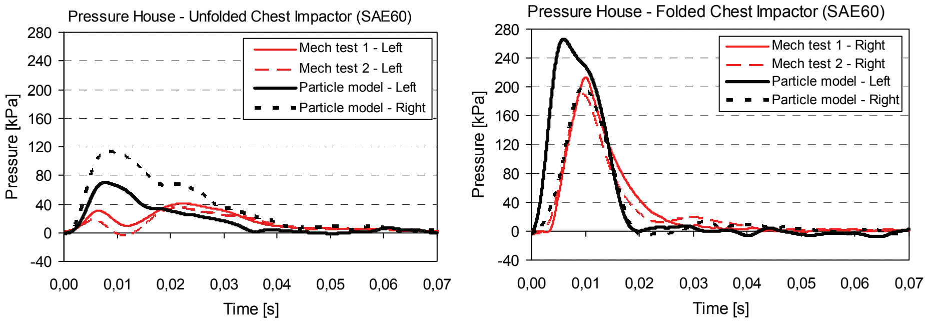


Figure 10. Unfolded and folded airbags with chest impactor, pressure in housing.

Although a higher initial pressure was predicted by the unfolded airbag model compared to the test, the response of the unfolded airbag model was too soft, which can be seen in both impactor acceleration and velocity (Figure 11 and 12). For the folded airbag model, the impactor acceleration peak was reached later than in the test, while the predicted velocity was in good agreement with the test results.

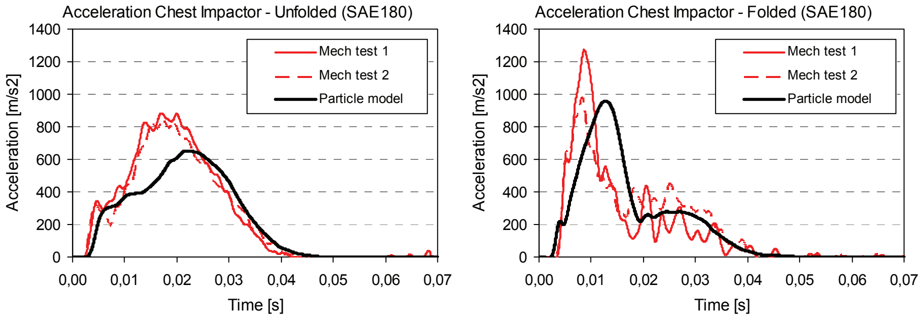


Figure 11. Unfolded and folded airbags with chest impactor, impactor acceleration.

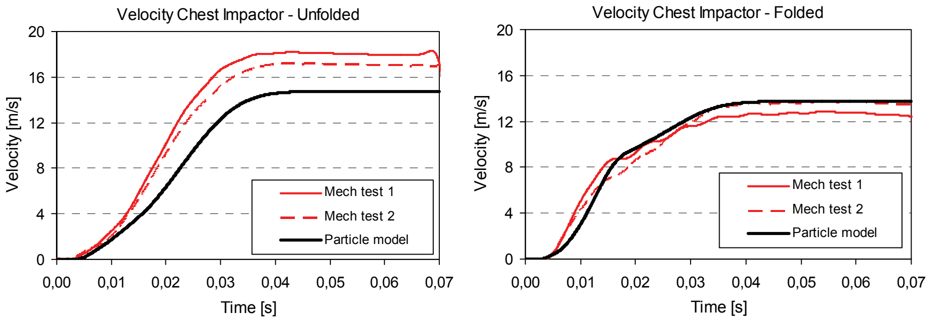
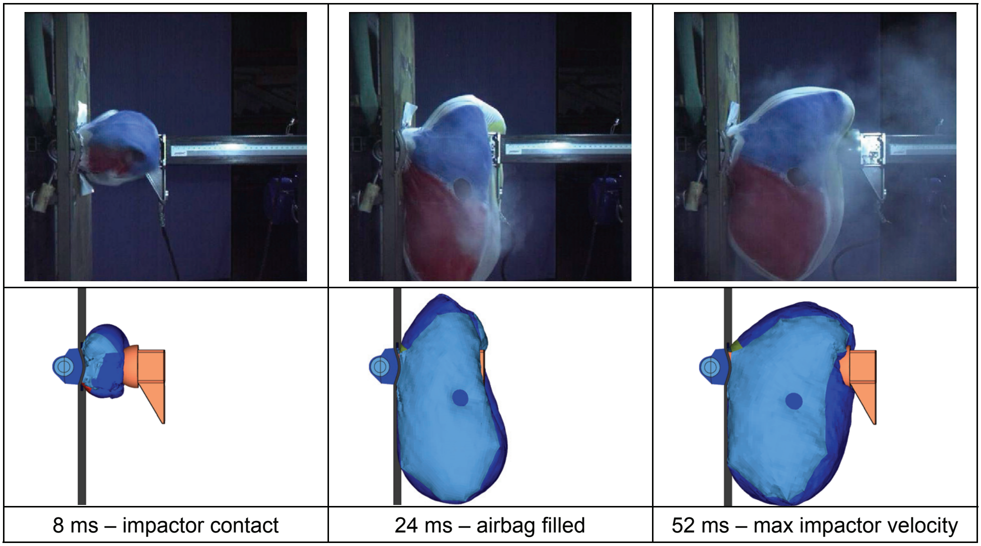


Figure 12. Unfolded and folded airbags with chest impactor, impactor velocity.

FOLDED AIRBAG INFLATION WITH HEAD IMPACTOR

In the head impactor load case, the airbag was allowed to inflate with a smaller obstruction compared to the chest impactor load case during the initial phase of the deployment. The airbag model using the particle method predicted the inflation of the mechanical airbag very well during the complete deployment phase (Figure 13).


8 ms – impactor contact

24 ms – airbag filled

52 ms – max impactor velocity

Figure 13. Folded airbag with head impactor, mechanical test versus airbag particle model.

The model showed a large pressure variation in the very early deployment phase up to 10 ms (Figure 14). After 10 ms, the level and shape of the airbag model pressure curve followed the test pressure well. The level of the peak acceleration was well matched, although a timing difference of 5 ms to the test can be observed.

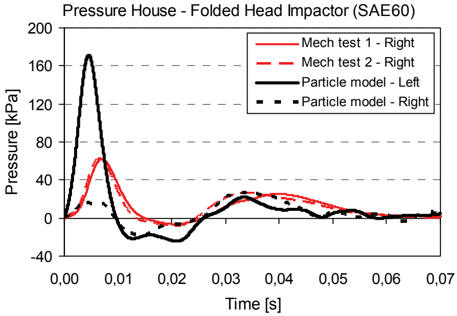


Figure 14. Folded airbag with head impactor, pressure in housing.

Both the impactor acceleration and final impactor velocity were very well predicted by the particle model. The impactor acceleration build-up after the first contact with the airbag was too large in the particle model, but the level corresponded well to the mechanical test (Figure 15). At 24 ms the airbag was fully inflated and fully supported by the wall. This allowed the forces to be effectively transferred to the head impactor, which was well predicted by the airbag model.

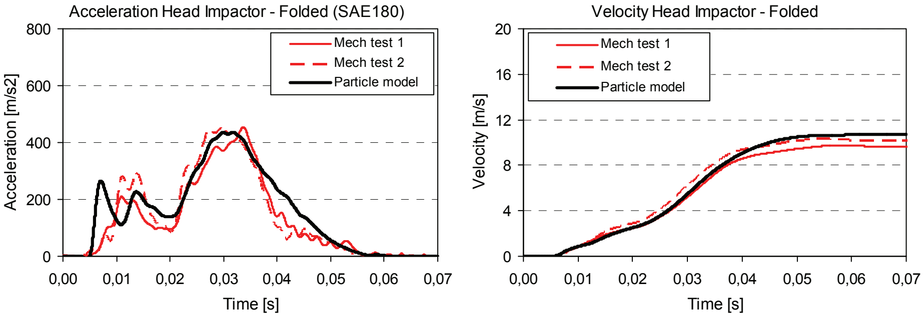


Figure 15. Folded airbag with head impactor, impactor acceleration and velocity.

DISCUSSION

Initial evaluation of the particle method for mathematical out-of-position modelling was carried out by means of static inflation tests and impactor tests of a frontal passenger side airbag. In the out-of-position load case, the occupant is initially positioned very close to airbag module and the interaction airbag-occupant occurs during the early deployment phase of the airbag. This was accounted for by the initially small distance between the airbag module and the impactors. The mathematical airbag model was inflated using mainly the LS-Dyna particle method, but a few comparisons to the control volume modelling approach were also carried out.

The flattening of the initially three-dimensional airbag was carried out by mathematical origami theory. The method generates the crease pattern which is needed to flatten the three dimensional airbag to a two-dimensional state with a minimum area loss. Given a polyhedron approximation of the three dimensional airbag, there exist numerous different crease patterns for folding a three-dimensional airbag flat. The origami folding method provides a way to systematically vary the crease pattern and evaluate the result in out-of-position load cases. With existing traditional tools, numerical folding is usually only carried out retrospective. However, the method can be improved if more general polyhedrons can be managed in the initial approximation of the airbag CAD model.

A simplified approach was adopted regarding the model leakage in the validation to the mechanical tests. In addition to the ventilation holes, the leakage from sources such as gas loss around the inflator, at fabric attachment in the housing, through the fabric and at seams, was lumped to the housing area of the airbag fabric. The size of the leakage was chosen based on the folded load cases with impactors and the same leakage size was applied to all simulated load cases. Due to varying pressure in different areas of the airbag volume, this leakage modelling approach was estimated to work well for the load cases with folded airbags and impactors, but less good for the load case with unfolded airbag and chest impactor. A more detailed leakage modelling, were the gas losses due to the different sources are separated, can improve the model results.

In the mechanical tests with chest impactor, the maximum kinetic energy of the impactor was 3.3 kJ for the unfolded airbag and 1.9 kJ for the folded airbag. The corresponding values that were predicted by the airbag particle model were 2.4 kJ and 2.1 kJ. Consequently, the test results showed a 74 % higher impactor kinetic energy for the unfolded airbag compared to the folded, while the airbag particle model predicted only 15 % higher kinetic energy for the same comparison. The energy losses in the mechanical tests were thus not fully taken account of in the model. The reason for the energy losses in the mechanical tests can be due to energy loss in the fabric unfolding process and energy loss due to increased leakage in fabric and seams exposed to the much higher pressure in the folded bag compared to the unfolded.

The pressure predictions in the housing were observed to vary more in the airbag particle model compared to the mechanical tests. One reason for this can be that, in the model, the pressure was monitored in a fabric area that was able to move during the inflation and was not fastened to the house wall as in the mechanical tests.

The pressures below atmospheric pressure which were observed in the test results during the very early phase of the airbag deployment can result in air being sucked in the housing area, leading to larger peak pressures due to the increased gas mass in the airbag. Also, some uncertainties exist regarding pressure measurements in an area very close to the generator outlet, especially during the very early inflation.

A small heat loss was present in the mechanical tank test, which was observed by the slightly decreasing pressure after the peak pressure 218 kPa at approximately 60 ms (Figure 6). The heat loss can be taken account of in the control volume analysis by adding a heat transfer factor, which results in a better prediction to the tank test. The tank test heat loss was not included in the airbag inflation simulations.

Although several improvement potentials have been identified, the models based on the particle method have been able to predict the airbag shape during inflation very well. Also the response results for the folded airbag load cases were good. The particle method handles small elements, complicated folding patterns and small creases very well, which is necessary for modelling of realistically folded airbags where the majority of the folds are represented. The particle method also has time advantages in preparation of the models. Next step will be to evaluate the particle method by means of airbag inflation with an occupant positioned close to the airbag.

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