ABSTRACT

The Curtain Airbag (CAB) is used currently to provide head and neck protection for the front-seat and rear-seat vehicle occupants during side-impact collisions and vehicle rollovers.

The coated fabric materials are used in CABs for occupant protection in side impact and rollover events. In this paper the design and development study of CABs is described by using simulation and physical tests. The mechanical properties for the airbag material are determined by uniaxial test in the fill and warp directions. Shear strength is also evaluated by using the uniaxial test, but the specimen is cut along 45º angle. These test values are used in the finite element (FE) simulations.

In this paper, a methodology of the design study is discussed. A Free Motion Headform (FMH) impacting a pole with a pillow shaped airbag is used in the design study. The influences of CAB design parameters such as pressure, chamber width, impact speed and hit location are evaluated. The simulations were correlated with actual tests under various conditions such as impact speeds, hit locations and various pressures in the airbag. The simulation results were compared to the physical test by Computer Aided Engineering (CAE) model correlation grading system.

INTRODUCTION

The CAB is increasingly used as a countermeasure in order to help protect the occupant during the side impact and rollover event. Unlike in the case of frontal impact, the space between the occupant and the deforming structure is much less. The CAB has to be deployed quickly and needs to be in position in a very short time—typically 20-30ms [1]. It is desirable for the CAB to be inflated for a longer duration so that adequate protection can also be provided in a rollover scenario. All these requirements demand that CAB fabric material have negligible leakage.

The fabric materials are typically coated with silicone to reduce the leakage through fabrics. Usually there is leakage through the stitch lines where the fabrics are sewn together. Newer sewing technology like the seamless method reduces the leakage through the seams.

In a normal driver and passenger airbag, the vents and permeability play a vital role in influencing the airbag performance. It was shown in [2], that the effect of permeability was the largest compared to other airbag parameters like the fabric modulus and the tether stiffness, using a Design of Experiments (DOE) study for a driver airbag. However, in the CAB the porosity is almost negligible because the CAB has to stay inflated for longer duration. Therefore, appropriate characterization of the mechanical properties of the fabric material is an important factor in evaluation of the performance using FE simulation.

Airbag FE simulations are used in design and development for occupant protection [1,2]. In this paper, experimentally determined material constants for fabric are used in the FE simulation. A Free Motion Head form (FMH) is used in the design and development process for CAB, which represents the occupant head motion in an actual crash. An impact speed of 24 to 29 kph is used to replicate the field conditions similar to those of FMVSS201 [3]. In the CAB design process, a Free Motion Headform (FMH) with pole impact test is performed to optimize the pressure in the airbag. Understanding the influence of the pressure is critical in designing an effective countermeasure under various impact speeds, thicknesses of the airbag and hit locations.

Many parameters such as airbag chamber width, pressure, speed of impact and hit locations influence the design of a CAB. Experimentally determining the influence of these parameters is time consuming and expensive. An alternative to this is to use numerical simulation in the design process.
In this study, a numerical design study using FE is performed with a pillow shaped dual-chamber airbag as a simplified representative of a CAB. Resultant head acceleration versus pressure charts for different cushion thickness under various head impact conditions was generated [4]. The correlation of the various head impact conditions with the physical test is discussed and a correlation grading system based on the procedure described in [5] is used to evaluate the simulation results.

**CAB MATERIAL MODEL AND TESTING**

The basic material compositions of the fabrics are nylon, polyester or other polymers. It is the manufacturing process, which changes the way the material behaves compared to the raw state. Fabrics are a web arrangement of extruded plastic threads, and its mechanical properties are different from the original material. This presents a challenge for FE modeling. Figure 1 shows an enlarged view of the fabric material structure.

![Image of fabric material structure](image1)

**Figure 1. Enlarged View of the Fabric Material Structure**

Yarns of fabric are weaved in a pattern shown in figure 1. The fill direction represents the fabric that is laid in the longitudinal direction. In the warp direction, the yarns are laid in the lateral direction. Normally the angles between both the directions are at 90°. Figure 2 shows the fill and wrap directions in a roll of fabric material. Fabric material exhibits directional physical properties in the fill and warp direction. One of the ways of characterizing the material is using the finite element method.

![Image of fabric roll](image2)

**Figure 2. Fabric Roll**

FE MODELING OF FABRIC MATERIAL

To generate the most accurate model to represent the fabric material, an FE model would have to be created at the thread level. As the individual threads are loaded, the interaction between them changes. Even though the material constitution at the molecular level does not change, the rearrangement of the threads results in changes in the global behavior, with a nonlinear response [6]. Figure 3 shows such a FE model.

![Image of thread level FE model](image3)

**Figure 3. Thread Level FE Model**

It is especially time consuming to create such a detailed model and will be computationally expensive in product development applications. In addition, it is very difficult to capture the leakage through the fabric, which is an important parameter in airbag applications. This type of modeling is difficult, if not impossible to be applied in a production environment. Under this condition, a membrane shell element is more practical in design and development studies. Commercial FE packages like LS-DYNA3D [7] solvers have a special fabric membrane element that is being used in airbag applications. To use such a material model macro level mechanical properties of the fabric have to be determined through physical test.

**FABRIC MATERIAL MODEL**

LS-DYNA3D material model FABRIC (MAT_34) is used to simulate the airbag material. It is a variation of the layered orthotropic material model [7]. To model the airbag as an orthotropic model, three material constants have to be provided. Assuming a plane stress condition, the material constitutive equations are given by [8]:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\tau_{12}
\end{bmatrix} =
\begin{bmatrix}
Q_{11} & Q_{12} & 0 \\
Q_{12} & Q_{22} & 0 \\
0 & 0 & Q_{66}
\end{bmatrix} \begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix}
\]

Where \(\sigma\) is the normal stress and \(\tau\) is the shear stress, the subscript refers to the principal material directions, i.e. the fill and warp directions. Also \(\varepsilon\) and \(\gamma\) are the strain components. The material elastic constants \(Q_{ij}\) are given by the following equations:
Where \( \frac{E_{1}}{1-V_{12}V_{21}} \)

\( Q_{12} = \frac{V_{12}E_{2}}{1-V_{12}V_{21}} - \frac{V_{21}E_{2}}{1-V_{12}V_{21}} \)

\( Q_{22} = \frac{E_{2}}{1-V_{12}V_{21}} \)

\( Q_{66} = G_{12} \)

\( Q_{11} = \frac{E_{1}}{1-V_{12}V_{21}} \)

\( Q_{12} = \frac{V_{12}E_{2}}{1-V_{12}V_{21}} - \frac{V_{21}E_{2}}{1-V_{12}V_{21}} \)

Where \( E_{1} \) and \( E_{2} \) are the Young’s modulus in the fill and wrap directions and \( G_{12} \) is the shear modulus of the fabric material. \( V_{ij} \) is the Poisson ratio of the material. Additionally in the LS-DYNA3D material model, fabric leakage can be accounted for. In addition, when modeling thin fabrics [6], buckling can result in an inability to support compressive stresses. A linearly elastic liner can also be included to reduce such tendency. However, for this CAB material, the leakage is almost negligible and therefore no leakage is specified.

The airbag tested is seamless and the leakage through the seams could be ignored. The linear option is not invoked in this study because the pillow airbag is not folded in the initial configuration. The orthotropic material axes can be defined by using AOPT option [6] in LS-DYNA3D solver, this allows to specify the fill and wrap direction. The mechanical properties are determined from the physical test.

MATERIAL TESTING

The mechanical properties of the fabric material can be determined from the uniaxial tensile testing. A predetermined fabric coupon with a width of 76.2mm and effective length of 203mm is cut along the fill and wrap direction. A sample with the above mentioned dimension is also cut at 45º directions from the fabric roll to determine the shear modulus. The coupons are then clamped at the edges and pulled at a loading rate of 150 mm per minute. The specimen is loaded until failure and the load versus elongation are recorded. Figure 4 shows a typical test setup.

From the load versus elongation curve the stress versus strain curve can be plotted. The stress versus strain curves for the fill, wrap and 45º material directions, are shown in figure 5. The Young’s modulus values can be calculated from the stress versus strain curves.

For the shear modulus since the fabric is tested using a sample cut at 45º material directions, the shear modulus can be calculated using the relation below [8].

\[
G_{12} = \frac{1}{\left(\frac{4}{E_{45}} - \frac{1}{E_{1}} - \frac{1}{E_{2}} + 2V_{12}\right)E_{1}}
\]

Where \( E_{45} \) is the modulus from the stress strain curve at 45º material direction.

HEAD IMPACT DESIGN STUDY

In the FMH impact test, a headform with a given initial velocity is made to impact an inflated airbag. Figure 6 shows a FMH physical test setup. In this case, the airbag is inflated through compressed air and a constant pressure is maintained. The responses such as HIC & 3ms clip acceleration of the headform are evaluated.

As a simplified representative of a curtain airbag (CAB), a dual-chamber pillow-shaped airbag is studied to provide general design guidelines for CAB. Resultant head acceleration versus pressure charts for different cushion thickness under various head impact conditions
Computer simulation models are used extensively as a complement to the physical tests to create the CAB design charts. This study also provides a method to validate the fabric material model. The study matrix for the design process is described below.

**CAB PERFORMANCE EVALUATION MATRIX**

A matrix of 84 runs with three different airbags with varying chamber thickness, (152 mm, 178mm and 203mm), two hit locations (center and seam), two speeds (24 kph and 29 kph) and seven different pressures (20, 30, 40, 50, 60, 80 and 100 Kpa) was studied. Figure 7 shows the matrix that was used in this study. The design criteria for this study were 1) the HIC value should be less than 700 and 2) the bag should not bottom out.

**Example Notation:**

152.40.C.24

152 – Size of Bag (mm)

40 – Pressure (Kpa)

C – Hit location (C-Center or S-Seam)

24 – Impact Speed (24 or 29 kph)

To provide enough representative test data for computer model correlation with minimal physical tests, a design of experiment (DOE) analysis was conducted to design the physical test matrix. A fractional factorial matrix consisting of 19 test configurations was generated from the DOE analysis. Each test was repeated twice to consider the test-to-test variations. Figure 8 shows the physical tests that were conducted based on the DOE study.

**FINITE ELEMENT MODEL OF TEST**

A FE model of the airbag with the rigid pole was used to simulate the test condition. The FTSS [10] FMH is used to simulate the experimental setup as shown in figure 9.
The airbag material is modeled in LS-DYNA3D using MAT_FABRIC (type 34) as mentioned in the previous section. The porosity of the fabric is assumed zero. Pole is modeled as a MAT_RIGID material and the degrees of freedom are constrained in all the directions. It is assigned the similar properties of steel for contact purposes. The Head form material properties are used as given by FTSS [10].

The headform is given an initial velocity corresponding to the test condition (24 kph or 29 kph). Optimal damping properties are used to stabilize the inflated bag in the numerical simulation.

**Inflator Mass Flow Calculation**

The airbag control volume in LS-DYNA3D is modeled as an AIRBAG_SIMPLE_AIRBAG_MODEL to simulate the shop air test condition. For this model, a mass flow curve needs to be estimated for each pressure condition in the airbag.

A baseline model of the airbag is run using AIRBAG_LOAD_CURVE option. This gives an estimate of the volume of the airbag. Using this estimated volume, the mass needed to get this pressure is calculated using the following ideal gas relationship.

\[ PV = mRT \]

- \( P \) = Pressure (Known quantity)
- \( V \) = Volume (Estimated from the baseline analysis)
- \( m \) = mass of the gas needed

\[ R = \frac{R}{MW} \] (\( R=8.314 \text{ J mol}^{-1}\text{K}^{-1} \), \( MW \) = molecular weight of the gas, air in this application)

- \( T \) = Temperature (ambient temperature is assumed to be constant)

Using the computed mass, a mass flow curve is generated as shown in Figure 10. The area under the curve should be equal to the total mass calculated. The mass is applied within first 10 milliseconds in this analysis. The mass flow curve has to be scaled up or down to get the exact pressure needed in the airbag and this normally takes one or two iterations.

**CORRELATION GRADING PROCESS**

A baseline FE model is created using the 178 mm bag and this is correlated to the 40Kpa, center hit and 29kph test conditions. Many more analyses were done to simulate the whole matrix for the 178 mm airbag. Only the pressure, speed and hit locations where changed in the model to generate the test conditions. The responses from this simulation matrix were compared to the physical test data. The correlation method described in [5] was used to compare and rank the responses. As mentioned in the previous section, a total of 19 physical test data (repeated twice) were available, and used for this correlation study.

The correlation method compares the simulation curve to the physical test curve and assigns a grade for each criterion in the dynamic response category. Each test result is compared and assigned a grade [5]. Figure 11, shows the grading criteria used for this study.

The overall grade for a specific bag (152mm, 178mm and 203mm) is arrived by taking the average of all the grades.

The grading charts for the airbags 152 mm, 178 mm and 203mm airbags are shown in the Tables 1, -3. In the table, abbreviated notations are used for the various cases. The expansion for the notation is given in figure 8.
### Table 1. Correlation Grading for the 152 mm Airbag

<table>
<thead>
<tr>
<th>Test#</th>
<th>Grading system</th>
<th>Overall Kinematics</th>
<th>Peak Magnitude</th>
<th>Avg Residual</th>
<th>Standard Deviation of Residual</th>
<th>Correlation Coefficient</th>
<th>0 Moment Difference</th>
<th>1st Moment Difference</th>
<th>2nd Moment Difference</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>152_40_C_24</td>
<td>Good</td>
<td>2.32%</td>
<td>4.15%</td>
<td>8.24%</td>
<td>0.984</td>
<td>10.00%</td>
<td>8.40%</td>
<td>10.00%</td>
<td>Good</td>
</tr>
<tr>
<td>2</td>
<td>152_60_C_29</td>
<td>Good</td>
<td>12.35%</td>
<td>2.35%</td>
<td>5.79%</td>
<td>0.991</td>
<td>7.20%</td>
<td>4.40%</td>
<td>3.00%</td>
<td>Good</td>
</tr>
<tr>
<td>3</td>
<td>152_100_C_29</td>
<td>Good</td>
<td>8.98%</td>
<td>1.19%</td>
<td>4.97%</td>
<td>0.993</td>
<td>4.00%</td>
<td>3.10%</td>
<td>2.50%</td>
<td>Exce</td>
</tr>
<tr>
<td>4</td>
<td>152_40_C_29</td>
<td>Good</td>
<td>31.30%</td>
<td>0.78%</td>
<td>4.16%</td>
<td>0.978</td>
<td>6.80%</td>
<td>8.00%</td>
<td>10.10%</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>152_60_S_29</td>
<td>Good</td>
<td>7%</td>
<td>0.31%</td>
<td>3.22%</td>
<td>0.998</td>
<td>1.20%</td>
<td>3.40%</td>
<td>4.50%</td>
<td>Exce</td>
</tr>
<tr>
<td>6</td>
<td>152_100_S_24</td>
<td>Good</td>
<td>6%</td>
<td>2.21%</td>
<td>3.51%</td>
<td>0.998</td>
<td>7.90%</td>
<td>8.90%</td>
<td>9.40%</td>
<td>Good</td>
</tr>
</tbody>
</table>

### Table 2. Correlation Grading for the 178 mm Airbag

<table>
<thead>
<tr>
<th>Test#</th>
<th>Grading system</th>
<th>Overall Kinematics</th>
<th>Peak Magnitude</th>
<th>Avg Residual</th>
<th>Standard Deviation of Residual</th>
<th>Correlation Coefficient</th>
<th>0 Moment Difference</th>
<th>1st Moment Difference</th>
<th>2nd Moment Difference</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>178_40_C_29</td>
<td>Good</td>
<td>6.80%</td>
<td>4.39%</td>
<td>7.88%</td>
<td>0.987</td>
<td>9.00%</td>
<td>10.60%</td>
<td>15.40%</td>
<td>Good</td>
</tr>
<tr>
<td>8</td>
<td>178_60_S_24</td>
<td>Good</td>
<td>6.25%</td>
<td>1.27%</td>
<td>4.35%</td>
<td>0.997</td>
<td>3.10%</td>
<td>1.20%</td>
<td>0.10%</td>
<td>Excellent</td>
</tr>
<tr>
<td>9</td>
<td>178_80_S_29</td>
<td>Good</td>
<td>5.14%</td>
<td>1.10%</td>
<td>3.10%</td>
<td>0.998</td>
<td>3.40%</td>
<td>6.10%</td>
<td>8.20%</td>
<td>Excellent</td>
</tr>
<tr>
<td>10</td>
<td>178_80_C_24</td>
<td>Good</td>
<td>6.34%</td>
<td>0.51%</td>
<td>3.89%</td>
<td>0.997</td>
<td>1.30%</td>
<td>1.60%</td>
<td>2.40%</td>
<td>Excellent</td>
</tr>
<tr>
<td>11</td>
<td>178_20_C_29</td>
<td>Good</td>
<td>21%</td>
<td>0.54%</td>
<td>5.34%</td>
<td>0.968</td>
<td>5.40%</td>
<td>11.20%</td>
<td>16.50%</td>
<td>Adequate</td>
</tr>
</tbody>
</table>

### Table 3. Correlation Grading for the 203 mm Airbag

<table>
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<tr>
<th>Test#</th>
<th>Grading system</th>
<th>Overall Kinematics</th>
<th>Peak Magnitude</th>
<th>Avg Residual</th>
<th>Standard Deviation of Residual</th>
<th>Correlation Coefficient</th>
<th>0 Moment Difference</th>
<th>1st Moment Difference</th>
<th>2nd Moment Difference</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>203_40_C_24</td>
<td>Good</td>
<td>11%</td>
<td>1.03%</td>
<td>5.38%</td>
<td>0.994</td>
<td>2.60%</td>
<td>1.40%</td>
<td>1.30%</td>
<td>Good</td>
</tr>
<tr>
<td>13</td>
<td>203_40_S_24</td>
<td>Good</td>
<td>2.30%</td>
<td>3.69%</td>
<td>8.75%</td>
<td>0.987</td>
<td>9.20%</td>
<td>4.80%</td>
<td>3.30%</td>
<td>Good</td>
</tr>
<tr>
<td>14</td>
<td>203_40_S_29</td>
<td>Good</td>
<td>5.80%</td>
<td>0.21%</td>
<td>4.31%</td>
<td>0.996</td>
<td>0.70%</td>
<td>3.60%</td>
<td>4.20%</td>
<td>Good</td>
</tr>
<tr>
<td>15</td>
<td>203_80_S_29</td>
<td>Good</td>
<td>8.40%</td>
<td>0.39%</td>
<td>5.30%</td>
<td>0.994</td>
<td>1.30%</td>
<td>5.60%</td>
<td>16.80%</td>
<td>Good</td>
</tr>
<tr>
<td>16</td>
<td>203_30_C_24</td>
<td>Good</td>
<td>7%</td>
<td>6.19%</td>
<td>6.05%</td>
<td>0.99</td>
<td>12.50%</td>
<td>12.50%</td>
<td>15.30%</td>
<td>Adequate</td>
</tr>
<tr>
<td>17</td>
<td>203_60_C_29</td>
<td>Good</td>
<td>7%</td>
<td>3.76%</td>
<td>5.44%</td>
<td>0.992</td>
<td>10.30%</td>
<td>9.90%</td>
<td>11.30%</td>
<td>Good</td>
</tr>
<tr>
<td>18</td>
<td>203_20_C_24</td>
<td>Good</td>
<td>11%</td>
<td>4.30%</td>
<td>7.53%</td>
<td>0.985</td>
<td>10.90%</td>
<td>11.50%</td>
<td>13.00%</td>
<td>Adequate</td>
</tr>
<tr>
<td>19</td>
<td>203_20_S_29</td>
<td>Good</td>
<td>5.45%</td>
<td>0.16%</td>
<td>4.58%</td>
<td>0.987</td>
<td>1.50%</td>
<td>5.10%</td>
<td>5.50%</td>
<td>Good</td>
</tr>
</tbody>
</table>

Table 1. Correlation Grading for the 152 mm Airbag

Table 2. Correlation Grading for the 178 mm Airbag

Table 3. Correlation Grading for the 203 mm Airbag
COMPARISON BETWEEN THE SIMULATION AND THE TEST RESULTS

The overlay between the tests and simulations for the resultant head acceleration of the head form for some of the cases are given in figures 12, 13, 14 and 15. In these figures, there are two test curves (repeats) and one simulation curve. In figure 14, the pillow airbag bottoms out and therefore the head impacts the pole, resulting in high resultant head acceleration values.

DISCUSSION

It can be seen from the stress versus strain curve in Figure 5, that the fabric material is nonlinear. For this study, a linear material model for the fabric was used. The modulus was computed at 10% strain. The assumed constant material properties at 10% strain level gave good correlation with the tests, similar assumptions were made by others [2,9]. The nonlinear behavior of the material can be modeled in the later versions (970) of LS-DYNA3D solver by giving directly the stress versus strain experimental data as the input. This method would eliminate the need for estimating the modulus or avoid the need for averaging the modulus. Proper test methods have to be performed to accurately capture the shear stress versus shear strain curve for generating material input data [7].

The maximum difference in peak resultant acceleration of the headform between the FE simulation and the test did not exceed 10% for most of the cases as shown in Tables 1-3. It can be seen from these tables that whenever the airbag was bottoming out, the difference in peak head acceleration between the simulation and test, was more than 10%. The reason for this discrepancy may be due to the material modeling of the pole as a rigid material. However, in reality the pole had some compliance, which was neglected in this analysis. In addition, test-to-test variation in the peak magnitude was also observed when the airbag bottomed out as shown in Figure 13. These discrepancies were ignored for the
design study since the bottomed-out bag violated the chosen design criteria.

CONCLUSION

Observations based on this application of this methodology to CAE design are as follows:

- Proper material characterization and appropriate boundary conditions are critical and sufficient for the prediction of headform performance.

- This study provided an understanding on the influence of design parameters such as the impact speed, hit location, chamber width and pressure on the performance of CAB.

- This component methodology shows promise in helping full system design by reducing iteration time and minimizing the number of physical tests.

ACKNOWLEDGEMENTS

The authors wish to thank the management of Delphi for the permission to publish this material. The authors express deep appreciation and thanks to their colleagues, Srini V Raman and Louise Zhang for their contribution.

REFERENCES