

Development of Side Curtain Airbag Deployment Simulation Technology Using CPM

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ABSTRACT

A technology for the simulation of the deployment of side curtain airbags that considers gas flow has been developed using the corpuscular particle method available in the crash analysis software LS-DYNA. The research developed an appropriate modeling method by elucidating the mechanism governing the behavior of the airbag during deployment, and increased the predictive accuracy of deployment simulations. Selecting four modeling parameters, the project analyzed their degree of effect on the behavior of the bag during deployment and identified input values for the parameters using simulations of airbag deployment. As a result, mesh size and time step were identified as the modeling parameters with the major effect on bag behavior. The determined computation input values for these parameters were employed in a side curtain airbag impactor simulation, and results for bag behavior during deployment and the impactor load displacement characteristic corresponded well with test results.

1. Introduction

Today, demand to make the transition to the use of simulations in automotive development is increasing, driven by the need to shorten the development period and reduce the number of prototypes created. In the case of simulations of occupant injuries in a collision, this necessitates modeling technologies for the vehicle, occupant dummies, seats, and safety equipment such as airbags. Simulation technologies for the vehicle framework and for plastic parts such as internal and external fittings have already been proposed by Takada, et al.⁽¹⁾ and Mae, et al.⁽²⁾, respectively. Among safety technologies, while examples of analyses of driver and passenger airbags are available, there have been few analyses of side curtain airbags (SCAB).

SCAB are components designed to protect vehicle occupants in the event of a side collision or a rollover. The period for which occupants' heads need to be protected during a rollover is longer than that for a side collision, and it is necessary to maintain gas pressure for several seconds. For this reason, SCAB employ a structure in which gas is not discharged to the exterior, but instead flows into a separate expanding section known as a sub-chamber in order to maintain pressure, as shown in Fig. 1. SCAB are normally stored folded in the roof; during a collision, gas flows from the inflator, and the airbag is deployed from a folded state (termed "static deployment"). These characteristics make consideration of gas flow essential when modeling SCAB for a simulation.

The Arbitrary Lagrangian Eulerian method (ALE), a

method which uses a computational grid, the Corpuscular Particle Method (CPM) and Smooth Particle Hydrodynamics (SPH) are known as gas flow computation methods employing LS-DYNA. The computation cost of the CPM and SPH is lower than that of ALE, and it is therefore suited to automotive collision computations, which necessitate a high volume of computation. SPH features an influence radius around the particles, which is a range in which the particles mutually interact. This makes it unsuitable for modeling bodies with small gaps, such as a folded airbag. CPM was therefore focused on in the research. According to previous studies of CPM conducted by Lee, et al.⁽³⁾ and Lien, et al.⁽⁴⁾, in the case of front airbags, the method displays a low level of accuracy in simulating the shape and internal pressure of the airbag during deployment. The shape and internal pressure of the airbag during deployment are important elements in the load displacement characteristic of the impactor, which restrains vehicle occupants, and an increase in simulation accuracy is therefore demanded. The fact that the particles used in the model are larger than gas molecules is generally indicated as the reason for the decline in accuracy, but the

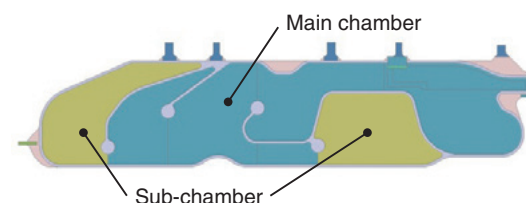


Fig. 1 SCAB structure

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mechanism of this decline has not yet been clarified.

This paper will therefore elucidate the mechanism governing the behavior of the airbag during deployment, discuss the development of an appropriate modeling method and the associated research process, and consider the results of a comparison of tests and simulations.

2. Development Goals

The following two main aims were set for the development of a SCAB simulation technology that considered gas flow:

- (1) Isolation and determination of the important modeling parameters that affect the static deployment of SCAB; and
- (2) The realization of a technology to increase the accuracy of prediction of the impactor load displacement characteristic.

3. Theory of Computation of Gas Flow and Self-Contact Force

This chapter will discuss two computation methods used in the simulation of the static deployment of SCAB: CPM, a computation method based on the motion of particles, a parameter that affects the deployment of SCAB; and a method of computing self-contact force, which is a reaction force generated when the fabric composing the SCAB is in contact with itself.

CPM is a computation method based on factors including the motion, pressure and temperature of gas. The general concept is grounded in molecular dynamics. Based on the ideal gas law, Eq. (1), and the pressure equation Eq. (2), which employs the average dynamic energy of the molecules and is in general use in the field of molecular dynamics, the velocity of the particles, v_{rms} , can be calculated using Eq. (4).

$$PV = nRT \quad (1)$$

$$P = \frac{1}{V} \sum_{i=1}^N m_i v_i = \frac{1}{3V} m \overline{v^2} = \frac{nMv_{rms}^2}{3V} \quad (2)$$

$$T = \frac{Mv_{rms}^2}{3R} \quad (3)$$

$$v_{rms} = \sqrt{\frac{3RT}{M}} \quad (4)$$

Here, P is pressure, V is the volume occupied by the gas, R is the gas constant, T is the thermodynamic temperature of the gas, M is molar mass, m is the mass of the gas molecules, N is the number of gas molecules in the volume V , and n is the mole number of the gas. The particles lose internal energy due to factors including adiabatic expansion. The velocity of the particles is recalculated based on these

changes in energy. The repetition of these calculations makes it possible to reproduce the expansion of the gas.

The self-contact force, F_{CF} , is expressed by means of Eq. (5), using a penalty method with ΔL as the degree of penetration in relation to the contact thickness and k as the penalty stiffness. In the research discussed here, the penalty stiffness was calculated using the following equations⁽⁵⁾:

$$F_{CF} = k_{CF}(t) \Delta L \quad (5)$$

$$k_{CF}(t) = 0.5 \cdot SLSFAC \cdot SFS \cdot \left(\frac{m_1 m_2}{m_1 + m_2} \right) \left[\frac{1}{\Delta t_c(t)} \right]^2 \quad (6)$$

Here, $SLSFAC$ and SFS are penalty coefficients, m_1 and m_2 are the mass of the elements, and Δt_c is the calculation time step.

4. SCAB Simulation using CPM

The SCAB simulation technology using CPM was constructed in the following three steps. First, the simulation computation input values for each component of the SCAB were determined. Next, using these characteristics, a SCAB static deployment simulation computation was performed, and the important modeling parameters affecting the deployment behavior of the SCAB were identified. Using the determined parameter values, test and simulation results for the deployment time and internal pressure of the SCAB were compared. Finally, using these computation input values, an impactor simulation was conducted, and the load displacement characteristic was compared in simulation and test results.

4.1. Determination of Simulation Computation Input Values for Components of SCAB

Before conducting a simulation of the static deployment of a SCAB, it is necessary to determine the mechanical and leakage characteristics of the SCAB fabric and the characteristics of the inflator. Material and leak tests of the fabric and inflator tank tests were therefore conducted in order to obtain test results and identify simulation parameters.

Tensile and shear characteristics were identified as the mechanical characteristics of the fabric. As Fig. 2 shows, the shape of the SCAB during deployment is a three-dimensional shape made up of a non-inflated area, A , and inflated areas,

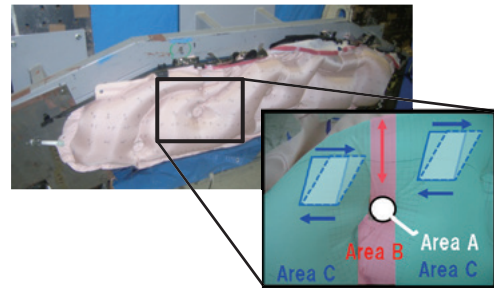


Fig. 2 Deformation of SCAB

B and C. Area B undergoes tensile deformation, and Area C undergoes shear deformation. Because the fabric is subjected to tension in the biaxial direction, a biaxial tensile test was conducted. The shear characteristic was calculated based on the picture frame test shown in Fig. 3⁽⁶⁾. The characteristics obtained from the respective tests were reflected in materials computation values for the SCAB model.

The fabric leakage characteristic was obtained using a blast tube test (Fig. 4). The blast tube was composed of two tanks, A and B, of differing diameters. Tanks A and B were separated by a film that functioned as a diaphragm. SCAB fabric was positioned at the end of Tank B. Air was introduced to Tank A, and when its internal pressure reached 280 kPa, the diaphragm burst and the air moved into Tank B, where it passed through the fabric and was discharged to the exterior. The leakage characteristic of the fabric was calculated based on the pressure history obtained from this test.

$$n = \frac{p_t V_t}{RT} \quad (7)$$

$$D = \frac{d}{V_t m_t} \quad (8)$$

Here, p_t is the pressure obtained from measurements, and V_t is the volume of the tube. The mole number, n , at this time is expressed by Eq. (7). Based on Eq. (7), if the leakage rate per unit of surface area is termed d , the leakage rate for the entire volume, D , can be calculated using Eq. (8)⁽⁶⁾. This leakage rate was set as the computation input value for the fabric leakage characteristic. A blast tube test simulation was conducted in order to verify the validity of the computation input values, and the results were found to display a good correlation with test results for pressure.

The inflator characteristic was obtained by calculating the rate of change in the mass of the inflator gas over time (the

mass flow rate) and the inflator outlet temperature in inflator tank tests. Using a tank with a single enclosed space of 28.3 L, the pressure of the inflator tank at ignition was measured. The mass flow rate of the inflator gas and the inflator outlet temperature were calculated based on the measured value⁽⁷⁾. A simulation of an inflator tank test was conducted using this mass flow rate and temperature as computation input values for the SCAB inflator, and the results were found to display a good correlation with test results for pressure.

4.2. Analysis of Static Deployment of SCAB

4.2.1. Static deployment conditions

In order to determine the modeling parameters that would have an effect on the behavior of the SCAB during static deployment, Model A (Fig. 5) was formulated to help elucidate the mechanism governing the behavior of the SCAB during deployment. Model A was rolled up and constrained at six points. Because the inflator was positioned at Point A in Fig. 5, the gas flowed in the direction shown by the arrows.

4.2.2. Identification of dominant modeling parameters

Model A was used to perform a static deployment simulation, making it possible to clarify the effect of the modeling parameters on the behavior of the SCAB during deployment. To make it possible to quantitatively analyze the relationship between the modeling parameters and the behavior of the SCAB during deployment, the time taken for the gas to pass Line A in Fig. 5 was defined as the deployment time.

The physical elements originating in the behavior of the SCAB during deployment are the self-contact force of the fabric, gas flow, and roll shape. There are four modeling parameters affecting these elements that a user is able to set: Time step, self-contact setting, particle number, and mesh size.

SCAB deployment time was therefore compared under the survey conditions for these four parameters shown in Table 1 (Fig. 6). In order to determine the degree of effect of the parameters, the minimum value for deployment time divided by the maximum value was regarded as the rate of change of deployment time. Calculated rates of change were 32% for mesh size, 32% for time step, 7% for the self-contact setting, and 10% for particle number. Mesh size and time step were therefore judged to be modeling parameters with a major effect on deployment time.

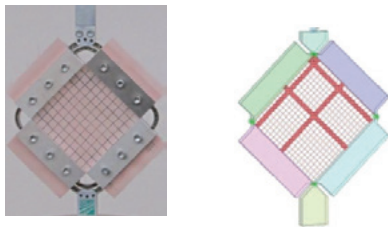


Fig. 3 Picture frame test

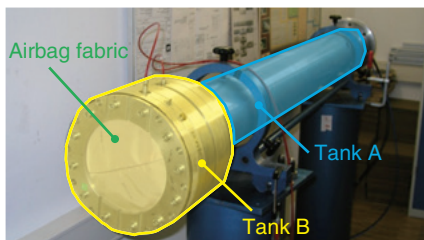


Fig. 4 Blast tube test

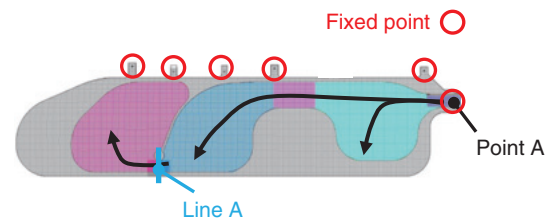
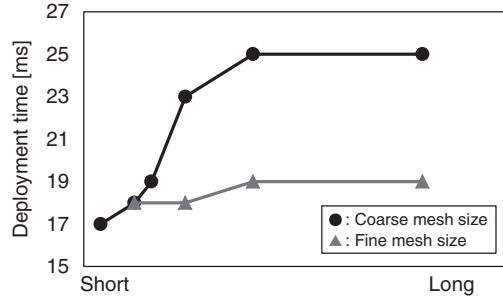


Fig. 5 Model A

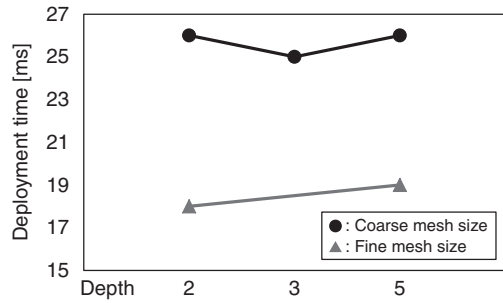
Table 1 Parameter survey conditions

Parameter	Survey conditions
Time step	-100%, -70%, -60%, 200%
Self contact setting	3 patterns
Number of particles	-10%, 200%
Mesh size	-50%, -75%

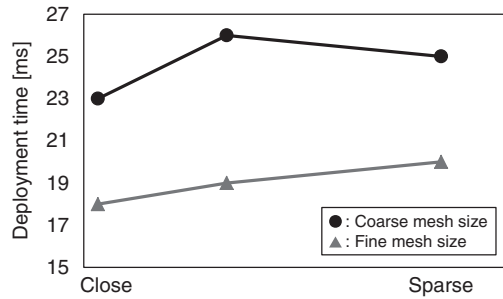
Next, in order to clarify the reason for the change in deployment behavior due to mesh size, a rolled model of an airbag with a single inflating chamber was formulated using



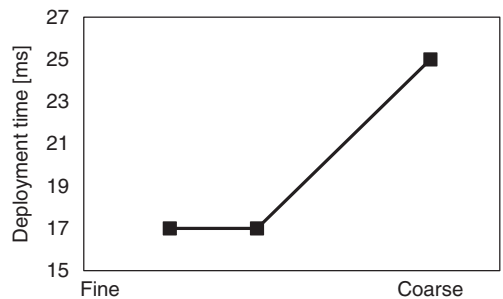
(a) Time step



(b) Self contact setting



(c) Number of particles



(d) Mesh size

Fig. 6 Effects of each parameter on deployment time

different mesh sizes. Figure 7 shows this airbag model prior to deployment and during deployment. When this model was statically deployed using the CPM, deployment behavior changed with the mesh size, as in the case of Model A. Two factors can be considered to be involved in this phenomenon.

First, the degree of freedom of nodal points increases. Figure 8 shows the status of the particles on the lower surface of the airbag fabric (hidden in the model) for two cases, Models α and β , which use the coarsest and the finest mesh sizes respectively, and that were created in order to identify the gas flow state. Compared to the coarse model, there are large numbers of particles flowing into the gaps in the fabric in the model using the fine mesh. Figure 9 shows sections from the centers of the models to provide a time history. In the case of the fine mesh, the roll diameter is compressed into concentric circles, and the gaps between the fabric increase. Because of this, a greater number of particles flow into those gaps. It is considered that this is because the degree of freedom of mesh nodal points increases, and the fabric on the interior of the roll is able to deform freely within the roll (Fig. 10).

Another factor is the increase in the degree of penetration in relation to the contact thickness of the fabric in the case of the coarse mesh. As Fig. 11 shows, with the

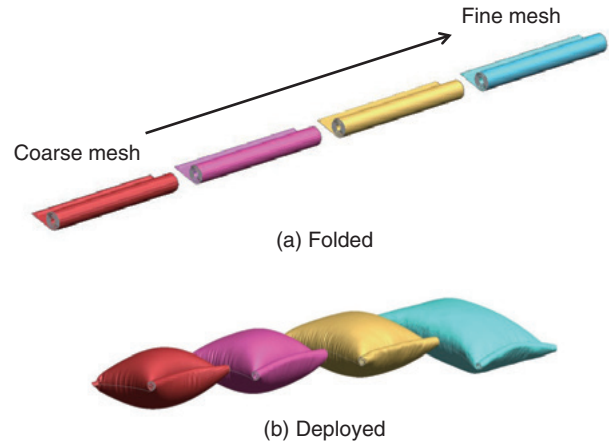


Fig. 7 Single-chamber model

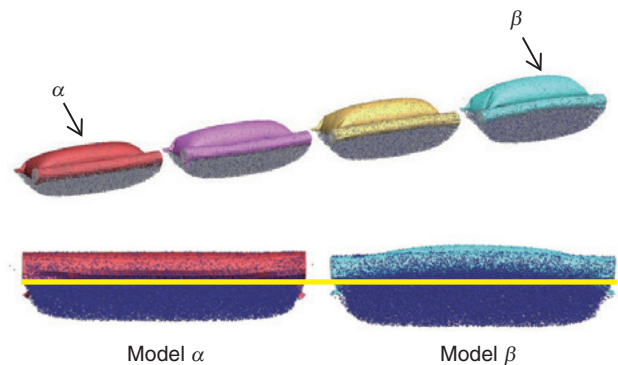


Fig. 8 Front view of single-chamber model

increase in penetration of the contact thickness of the fabric when the coarse mesh is used, it is possible that the contact reaction force will act to resist the unfolding of the SCAB.

In the case of time step, Eq. (5) showed that this parameter has an effect on the self-contact force of the airbag. It was predicted that an increase in time step would reduce the contact force, thus delaying deployment. The results shown in Fig. 6(a) correspond to this prediction, indicating the necessity of setting an appropriate value for this parameter. Because there is a high rate of penetration between the fabric sections when the coarse mesh is used, the effect of the time step is significant, with a rate of change in deployment time of 32%. In the case of the fine mesh, the rate of change in the behavior of the bag during

deployment dropped to 5%, indicating that the use of a fine mesh counteracted the effect of this parameter.

4.2.3. Verification of parameter values

With the mesh size and the time step set at fixed values, the fluctuations in behavior during deployment disappeared, and deployment time converged on a fixed value. A mesh size and time step that would commence the convergence with minimal computation time were selected, and the simulation results were compared with test results. Figure 12 shows the behavior of the SCAB at the time when the gas has passed Line A in Fig. 5. In both sets of results, the gas passes Line A at 18 ms, and results for deployment time match. Figure 13 shows a comparison of the time

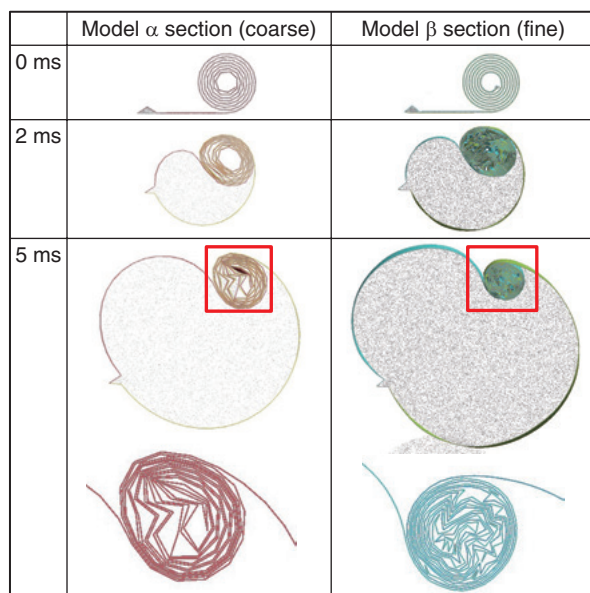


Fig. 9 Sections of centers of single-chamber models

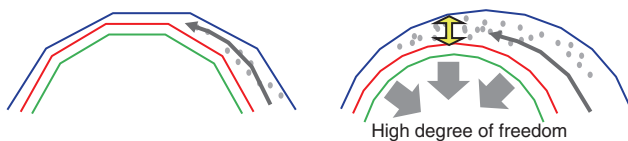


Fig. 10 Effects of mesh size (Degree of freedom)

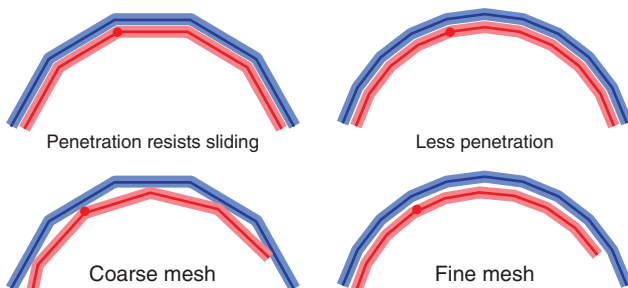


Fig. 11 Effects of mesh size (Penetration)

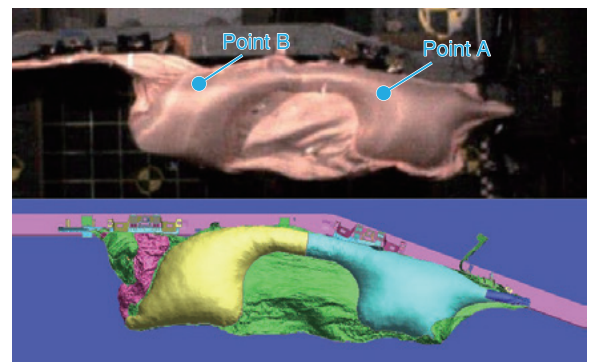
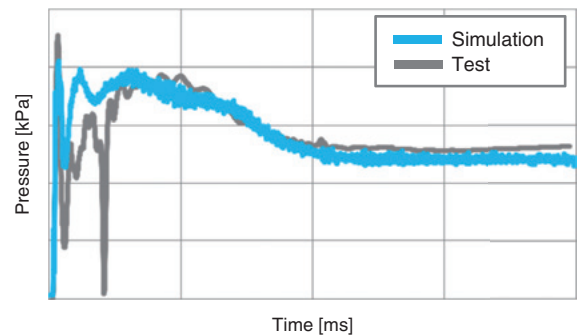
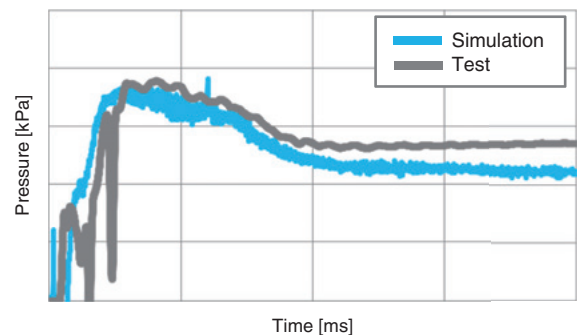


Fig. 12 Model A deployment at 18 ms



(a) Pressure at Point A



(b) Pressure at Point B

Fig. 13 Pressure during Model A deployment

history of internal pressure in the airbag. The simulation and the tests produced similar results for internal pressure.

4.3. Comparison of Impactor Performance

Using two SCAB that are fitted in different vehicles (Model B, fitted in sedans, and Model C, fitted in SUVs), impactor simulations were conducted based on the modeling computation input values discussed above, and results were compared with test results with a focus on the load displacement characteristic. The conditions for the impactor test were an impactor mass of 4.5 kg and an initial velocity of 32 km/h.

Model B SCAB, which is employed in sedans, is stored folded in a roll. The diameter of the folded roll is 30 mm, and the inflator is positioned at the rear end of the vehicle. Using this SCAB, two simulations were conducted: Case A, using standard setting values for mesh size and time step; and Case B, using the setting values obtained through this research, and the results were studied. Figure 14 shows a time history of images of static deployment of the SCAB during the impactor test, and compares simulation results with test results. In Case A, deployment time was slower in the simulation results than in test results, and the volume of the SCAB was lower at the points at which the impactor contacted it.

Because of this, the impactor load for Case A was considered too high in the impactor load displacement characteristic shown in Fig. 15. For Case B, simulation results matched well with test results for SCAB deployment time and the impactor load displacement characteristic, and the load displacement characteristic of the impactor

received from the airbag also matched test results well.

Like Model B, the SUV-type SCAB, Model C, is stored rolled, and when rolled its diameter is 33 mm. The inflator is positioned close to the center of the vehicle, and the gas flow differs from the sedan-type SCAB, with gas flowing from the inflator to the front and rear of the vehicle.

Results for the load displacement characteristic from an impactor simulation conducted using the modeling settings identified in this research were compared with test results. Even in the case of a gas flow differing from the sedan-type SCAB, simulation results for airbag behavior during deployment (Fig. 16) and impactor load displacement characteristic (Fig. 17) displayed a good correlation with test results.

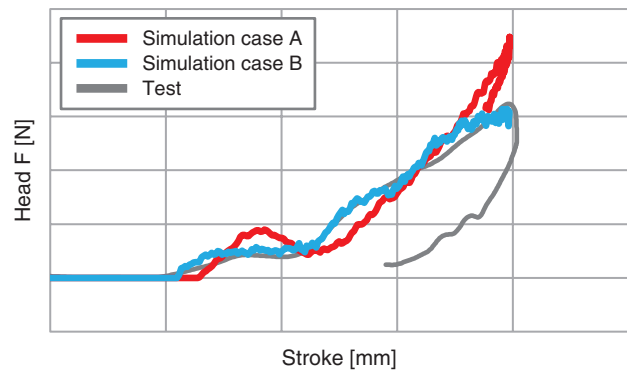


Fig. 15 Load-displacement history of impactor (Model B)

	CAE		Test
	Case A: Coarse mesh	Case B: Fine mesh	
15 ms			
17 ms			
20 ms			
25 ms			

Fig. 14 Deployment behavior of sedan-type SCAB (Model B)

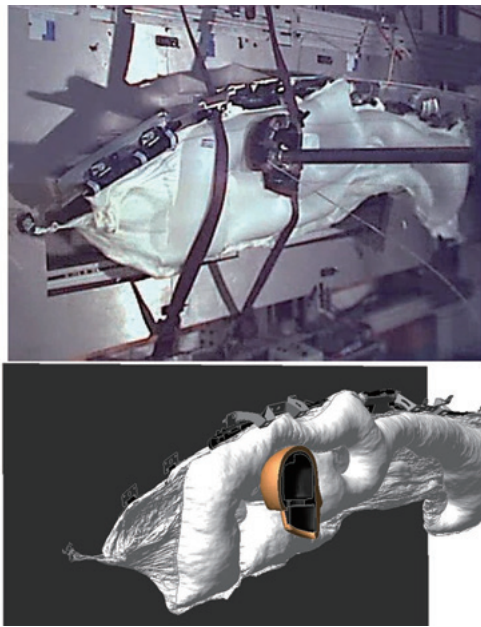


Fig. 16 Deployment behavior of SCAB SUV-type (Model C)

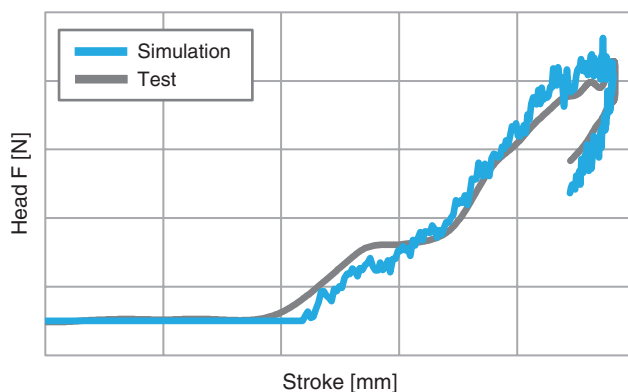


Fig. 17 Load-displacement history of impactor (Model C)

5. Conclusion

A technology for the simulation of the deployment of SCAB, which considers gas flow, has been developed using CPM. This project produced the following outcomes.

- (1) Mesh size and time step were identified as the modeling parameters with the greatest effect on the static deployment time for SCAB, and the mechanism governing the behavior of the SCAB during deployment was elucidated, making it possible to develop a method of setting appropriate modeling parameters.
- (2) It was possible to use simulations to predict the behavior of SCAB during static deployment and the impactor load displacement characteristic.

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