Using JFOLD and *AIRBAG_CPG to Study the Effect of Fold Pattern on Curtain Airbag Deployment

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1 Abstract

JFOLD® is a software tool for simulation-based airbag folding in Ansys LS-DYNA®. **`*AIRBAG_CPG`** (Continuum-based Particle Gas) is a new solver for airbag deployment analysis, implemented in Ansys LS-DYNA R16. It demonstrates significant potential for predicting deployment by enabling high-precision simulation of gas flow within complex airbag structures. Curtain airbags play an important role in vehicle safety systems. They are carefully folded and stored within the trim and roof side rail and must deploy quickly into the narrow gap between the occupant and the door when a side collision is detected. If the airbag interferes with components such as trim, guides or brackets during deployment, the deployment speed and direction may be significantly hindered, potentially compromising occupant protection. To avoid such issues, engineers devote considerable effort to optimising the folding pattern to ensure smooth and reliable deployment. In this study, we present a method for easily designing and optimising different folding patterns for a single curtain airbag using the latest features of JFOLD. Subsequently, the deployment performance of each folding pattern is evaluated using **`*AIRBAG_CPG`**, based on a baseline model validated against physical test results.

2 Introduction

Airbags are among the most important safety devices for mitigating occupant injuries in automobile collisions. Various types exist, including driver, passenger, side, and curtain airbags. These airbags are efficiently stored within the limited space of the vehicle and are deployed instantaneously upon collision detection to protect the occupant's head, chest, lower legs and other body regions. In particular, for curtain airbags, the design of the folding state and storage position is critically important, as deployment speed and direction significantly affect occupant protection performance under complex conditions such as side or oblique impacts. If interference occurs during deployment with vehicle components such as trim, guides, or brackets, the deployment behaviour may be hindered, resulting in reduced protective performance. To avoid such issues, engineers spend considerable time optimising the folding pattern to ensure reliable and consistent deployment.

In this study, a curtain airbag folding model was constructed using JFOLD [1-7], a simulation-based folding tool in Ansys LS-DYNA. Furthermore, deployment analysis was conducted using **`*AIRBAG_CPG`** (Continuum-based Particle Gas), a new gas dynamics solver implemented in Ansys LS-DYNA R16 [8][9]. **`*AIRBAG_CPG`** enables high-precision simulation of gas flow inside the airbag based on the Navier-Stokes equations and has demonstrated high utility in predicting deployment behaviour in airbags with complex structures. A baseline model was first created to match the results of a physical static deployment test. Three folding patterns (Z-fold Type 1, Z-fold Type 2, and Roll-fold-only) were then designed using JFOLD based on this model. Deployment analysis was performed for each pattern using **`*AIRBAG_CPG`**, and the influence of folding configurations on deployment behaviour was evaluated. The objective of this study is to clarify the relationship between folding design and deployment performance, and to demonstrate the effectiveness of JFOLD and **`*AIRBAG_CPG`** in future airbag design and development.

3 Introducing JFOLD

3.1 Overview of JFOLD

JFOLD is a software tool developed by JSOL Corporation to support simulation-based airbag folding modelling. This tool operates as a JavaScript application within PRIMER developed by Oasys Ltd., and each folding step is simulated using Ansys LS-DYNA. JFOLD features an intuitive and user-friendly graphical user interface, making it easily accessible to users with basic knowledge of Ansys LS-DYNA and PRIMER. Its design enables engineers to efficiently model and simulate realistic airbag folding sequences, thereby contributing to improved accuracy and productivity in airbag deployment analysis.

Features of JFOLD
- Manages folding steps using a flowchart-style graphical interface
- Supports one-click automatic tool positioning (auto-positioning function)
- Allows previewing of tool behaviour before execution
- Enables easy reuse of tools across multiple folding steps
- Includes sewing simulation for generating 3D airbag geometries
- Powerful morphing tool
- Generates analysis models that avoid initialization errors in Ansys LS-DYNA
- Preserves shell element size of the reference (pre-folded) geometry during folding
- Allows reuse of folding paths for new airbag geometries
- Offers an automatic folding execution system (under continuous improvement)

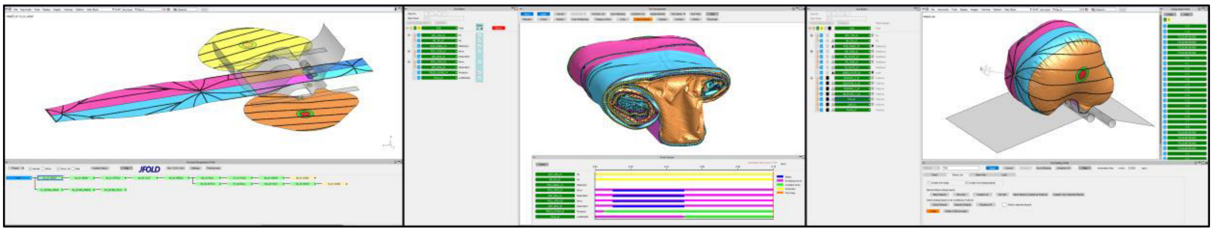

Fig.1: JFOLD’s GUI: process management, tool management & tool setting panels

3.2 Folding Process Management System

In JFOLD, the airbag folding process is managed as a sequence of discrete “steps.” Each step corresponds to a single LS-DYNA analysis, simulating realistic folding operations such as fabric deformation, panel stitching, and material relaxation. The airbag model is passed from one step to the next, inheriting the deformed geometry obtained in the previous step. Folding steps are highly flexible and can be edited, duplicated, or branched at any stage, allowing engineers to easily explore and compare multiple folding patterns. The deformation of the airbag is controlled using “tools,” which can be copied across steps, imported from the built-in tool library, or created by the user. These tools enable precise control over the folding process and contribute to the accurate reproduction of real-world airbag shapes.

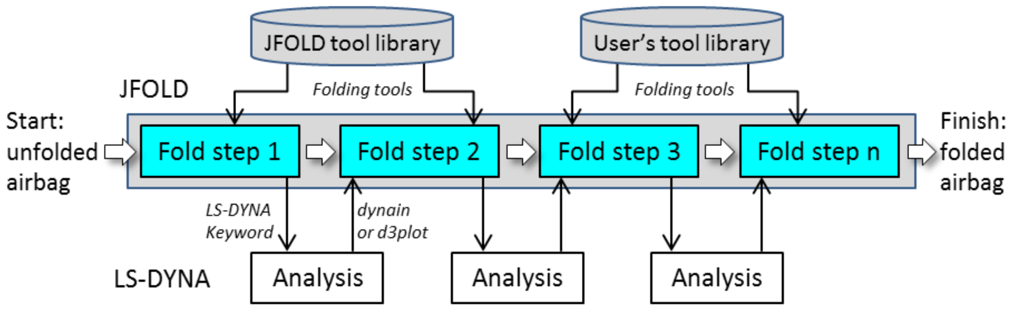

Fig.2: Schematic of one folding process using JFOLD

3.3 Development and Evolution of JFOLD

Since the release of Version 1 in 2013 [1], JFOLD has been updated annually with major upgrades and continuous improvements [2-7]. The software is widely used by major automotive manufacturers and airbag suppliers in Japan, and is also marketed internationally with users overseas. Each version adds new features based on user feedback, ensuring the software evolves to meet engineering needs. Version 12, released in October 2025, introduced a redesigned graphical interface for improved usability. The interface is in English, with help documentation and training manuals available in both Japanese and English.

4 Overview of the CPG Airbag Solver

The CPG (Continuum-based Particle Gas) airbag solver, available in Ansys LS-DYNA from version R16.0, enables high-fidelity simulation of gas flow based on the Navier-Stokes equations. It allows accurate prediction of gas velocity and pressure distribution within complex airbag structures. During analysis, particles are automatically generated inside the airbag volume and on fabric shell elements to model gas-fabric interactions precisely. The particle spacing (HLEN) is user-defined. While finer spacing improves accuracy, it increases particle count cubically, leading to higher computational cost. Therefore, appropriate spacing is essential for efficiency. Future versions are expected to include automatic particle refinement to balance accuracy and cost. Compared to the conventional CPM (Corpuscular Particle Method), CPG requires more computational resources but offers better accuracy in narrow flow regions. For example, in curtain airbags with long, narrow channels, CPM can simulate gas flow using options like IAIR=4 [3][10], but its probabilistic particle behaviour limits accuracy. Increasing CPM particle count improves results but negates its cost advantage. CPM also struggles with small vent holes, often resulting in insufficient exhaust flow. Although enhanced vent options can help, complete resolution is difficult. In contrast, CPG can more easily improve accuracy by increasing particle density around vent holes.
CPM’s main advantage is its low computational cost. Therefore, a hybrid approach is recommended: use CPM for initial simulations to identify promising designs, followed by detailed evaluation with CPG to achieve a balance between accuracy and efficiency.

5 Curtain Airbag Model Construction

In this study, multiple curtain airbags of identical specifications, commonly installed in compact passenger vehicles in Japan, were procured and modelled for analysis. Observation of the folding method confirmed that the airbags were primarily folded in a rolled configuration. To further investigate the internal structure, the airbags were disassembled, revealing that a diffuser was placed inside the chamber where the inflator is inserted. It was also confirmed that the airbags were mounted to the vehicle body using tabs. Based on these findings, accurate geometric data of the airbag were created using reverse engineering techniques. The left side of Figure 3 shows the actual curtain airbag, while the right side shows the corresponding analysis model. The diffuser inside the airbag was also included in the model.

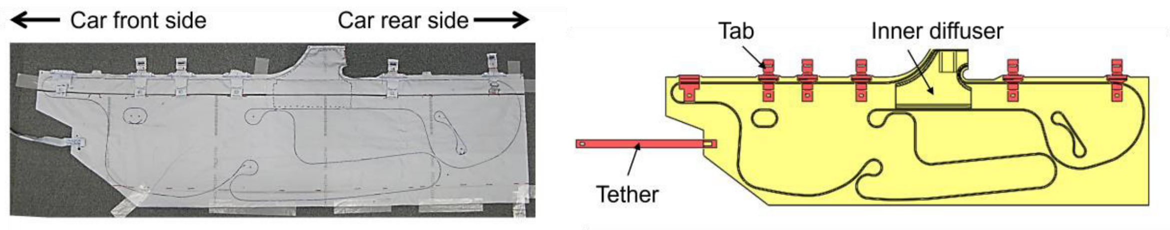

Fig.3: Actual curtain airbag (left) and reverse-engineered simulation model (right)

Subsequently, a folding model was constructed using JFOLD with the objective of faithfully reproducing the actual folded state of the airbag. Figure 4 shows the folding process calculated using JFOLD. First, a roll-folding operation was performed, followed by a fitting step to install the inflator. Next, a deformation step was carried out to package the airbag into the roof side rail (package space) of the vehicle. Finally, a step was added to install the guide components.

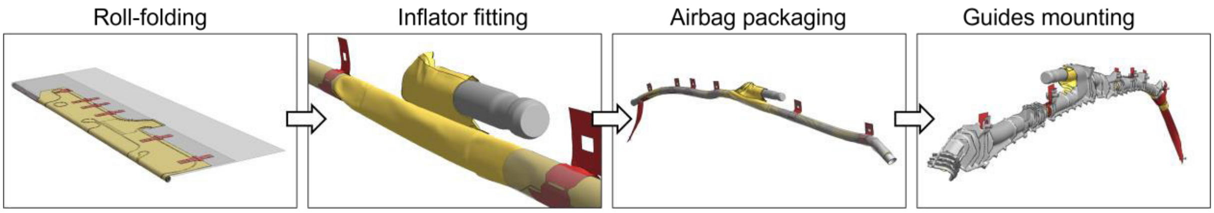

Fig.4: Curtain airbag folding process

The inflator's mass flow rate was measured through a tank test conducted by an airbag supplier. Fabric material properties were based on representative values from previous airbag development projects by JSOL Corporation and Arup. The curtain airbag is stored along the roof side rail and mounted using plastic guides, which help secure the airbag and control its deployment direction. These plastic components were digitized using a 3D scanner and meshed with tetrahedral elements, with generic plastic properties assigned. The airbag is fixed to the vehicle using tabs designed to rupture during deployment, enabling controlled inflation.

6 Validation of the Curtain Airbag Model

A static deployment test of the curtain airbag was conducted by the Japan Automobile Research Institute. The curtain airbag was mounted on a rigid fixture together with the plastic guide components, and the deployment behaviour was recorded from multiple angles using high-speed cameras. Deployment analysis was performed using the curtain airbag analysis model constructed in the previous section. The upper part of Figure 5 shows the mounting condition in the physical test, while the lower part shows the analysis model that faithfully reproduces the test setup. Figure 6 compares the deployment behaviour between the physical test and the CPG airbag simulation at 5-millisecond intervals.

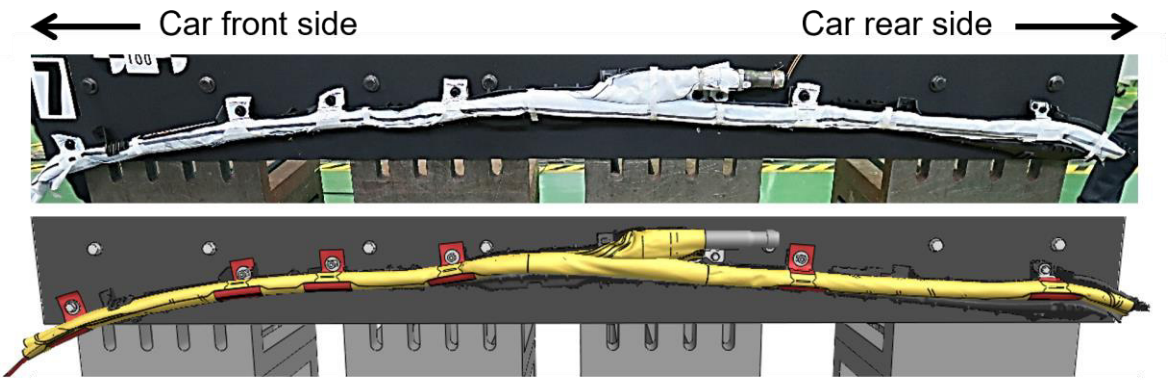

Fig.5: Curtain airbag (top) and simulation model (bottom) for static deployment test

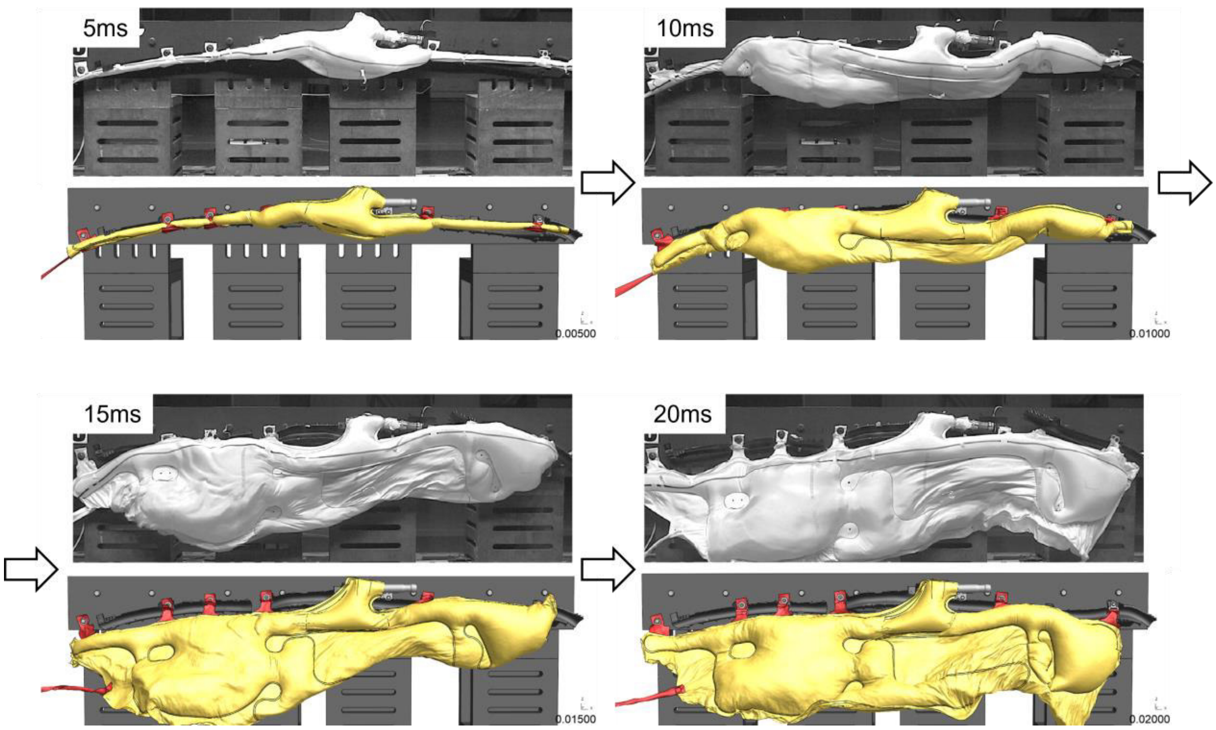

Fig.6: Comparison of deployment behaviour between physical test (top) and simulation result (bottom)

In the process of aligning the simulation with the physical test, discrepancies were observed in the early-stage gas jetting behaviour around the inflator. To address this, the initial portion of the mass flow rate curve was adjusted. However, the total mass of discharged gas was not changed in order to maintain consistency with the tank test data. It should be noted that the accuracy of mass flow rate measurement in tank testing can be affected by the positioning of pressure sensors, particularly when capturing localized pressure spikes during the initial ignition phase. Therefore, further improvement in measurement techniques is required to enhance the reliability of inflator characterization. For reference, deployment analysis was also conducted using the conventional CPM (Corpuscular Particle Method) with IAIR=4, and similar deployment behaviour was confirmed. Thus, both solvers were able to reproduce the deployment behaviour, but CPG demonstrated higher accuracy in simulating gas flow in narrow regions.
Furthermore, as shown in Figure 7, it was confirmed that the gas flow was obstructed by the tabs, and that the timing of tab rupture significantly influenced the deployment behaviour.

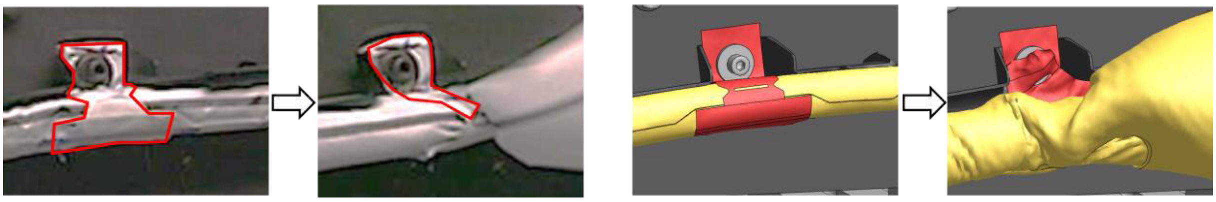

Fig.7: Tab rupture behaviour in physical testing (left) and reproduced in simulation (right)

Therefore, in the analysis model, the rupture parameters of the tabs were adjusted to reproduce the gas flow observed in the physical test, thereby reflecting this effect. Based on the results, it was found that the timing of tab rupture is a critical factor; however, in actual conditions, variability in tab rupture behaviour may occur. To improve the consistency of deployment performance, it is desirable to consider mounting methods that reduce such variability.

7 Influence of Curtain Airbag Folding Patterns

7.1 Role and Importance of the Z-Fold

Curtain airbags are designed to deploy into the narrow space between the occupant and the door in the event of a side collision. Therefore, both the deployment speed and deployment direction are critical factors that significantly affect occupant protection performance. If deployment is too slow, the airbag may not fully inflate before the occupant contacts the door or pillar, resulting in reduced protective effectiveness. On the other hand, if the deployment direction is oriented toward the occupant, the airbag may interfere excessively, potentially causing harmful effects. Curtain airbags are typically stored using a roll-fold configuration; however, in some cases, a Z-fold is added to control the deployment speed and direction. The Z-fold is usually positioned on the guide side, and by directing the initial gas flow into the Z-fold region, the airbag can be pushed outward more quickly. This design contributes to early deployment and directional control, making the Z-fold an important design parameter for optimising airbag performance.

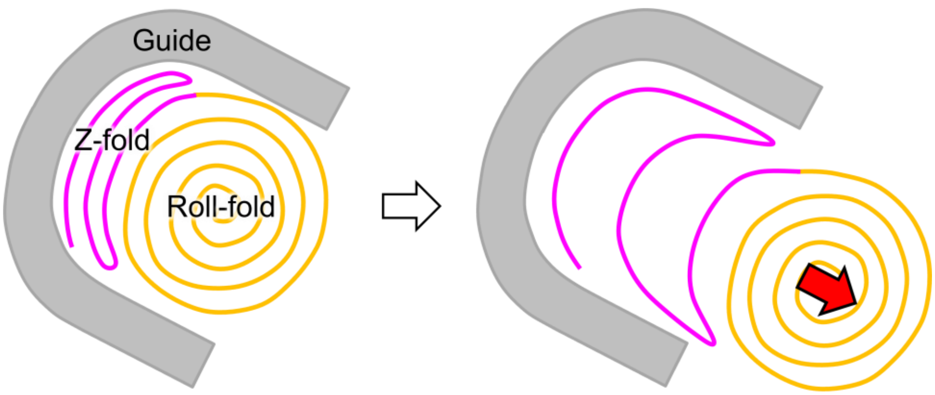

Fig.8: Effect of Z-fold on promoting deployment of the roll-folded section toward the cabin interior

7.2 Creation of Z-fold Models

Using the model validated against static deployment test as a baseline, a comparative analysis was conducted with folding patterns of different Z-fold designs. Although no physical tests were performed with modified folding patterns, the study was considered valid as these Z-fold designs are commonly used in industry and the baseline model was consistent with the experimental data. To eliminate the influence of tab rupture timing, the tabs were removed from all analysis models, and the airbag was attached to the vehicle in a simplified manner using spring elements. Figure 9 shows the airbag with a Z-fold configuration. The left side of the figure illustrates the region where the Z-fold is applied, while the right side shows the resulting Z-folded geometry. It can be observed that the region into which the gas is first injected from the inflator is folded in a Z-shape.

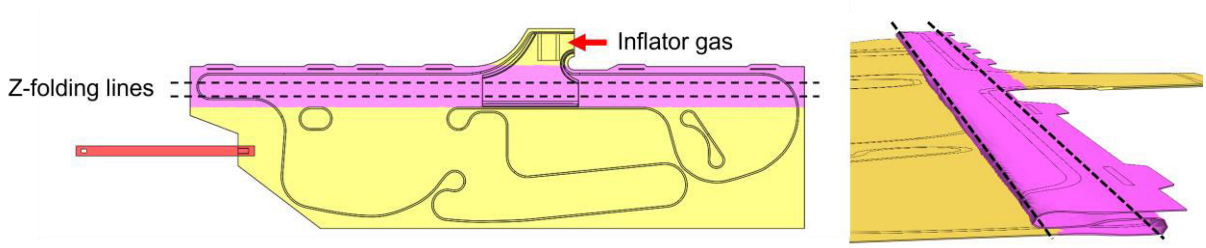

Fig.9: Z-fold region (left) and Z-folded geometry (right)

Three different folding patterns were created using JFOLD, as described below:

- Z-fold Type 1 (left side of Figure 10):
  The Z-fold was positioned along the guide. This configuration was designed to direct the initial gas flow into the Z-fold region, thereby pushing the airbag outward more forcefully and at an earlier stage.

- Z-fold Type 2 (center of Figure 10):
  The Z-fold was placed above the guide. Although the size of the Z-fold was the same as in Type 1, this configuration was designed with an emphasis on controlling the deployment direction.

- Roll-fold-only (right side of Figure 10):
  The airbag was entirely roll-folded and used as a reference for comparison with the Z-fold configurations. Notably, the baseline model also employed a similar folding pattern.

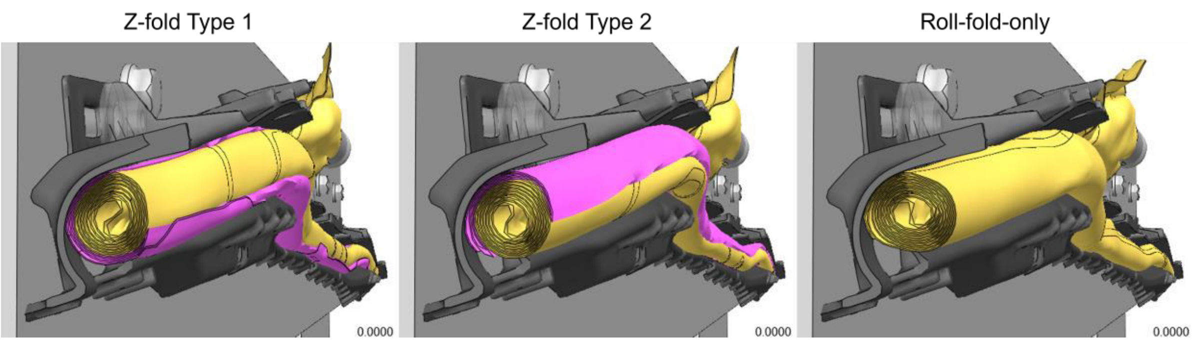

Fig.10: Folding types with Z-fold sections highlighted in pink

Figure 11 shows the folding process management (flowchart) in JFOLD for the creation of the three folding models.

Fig.11: JFOLD folding process management using flowchart interface

The folding analysis for the Z-folded geometry shown in Figure 9 was conducted in [01_04 ZFOLD]. Subsequently, the process branched into [03_05 WRAP] and [03_06 WRAP], where the Z-fold placement was modified to generate Z-fold Type 1 and Type 2, respectively. The following steps, including inflator fitting, airbag packaging into the roof side rail and guide mounting, were performed using the same folding process. Because identical tool settings were applied across these steps, configuration was quick and straightforward, demonstrating that JFOLD's folding process management system enables efficient creation and modification of various folding patterns with minimal effort.

7.3 Comparison of Deployment Behaviour Based on Folding Patterns

Deployment analysis was conducted using the CPG airbag solver implemented in Ansys LS-DYNA R16.1. The particle spacing (HLEN) was set to 2.5 mm, matching the mesh size of the airbag fabric. This value was selected based on the recommendation that HLEN should be equal to or smaller than the fabric mesh size 2.5mm. Figure 12 shows a cross-sectional view of the airbag at 3.5 milliseconds, corresponding to the region near the occupant's head. In Z-fold Type 1 and Type 2, gas first entered the Z-fold region on the guide side, pushing the roll-folded section, which had not yet received gas, outward toward the cabin side (right side of the image). In Type 2, the Z-fold was positioned slightly higher, resulting in the roll-folded section being pushed slightly downward compared to Type 1. In the Roll-fold-only case, gas initially entered the cabin-side region opposite the guide, pushing the roll-folded section toward the guide side.

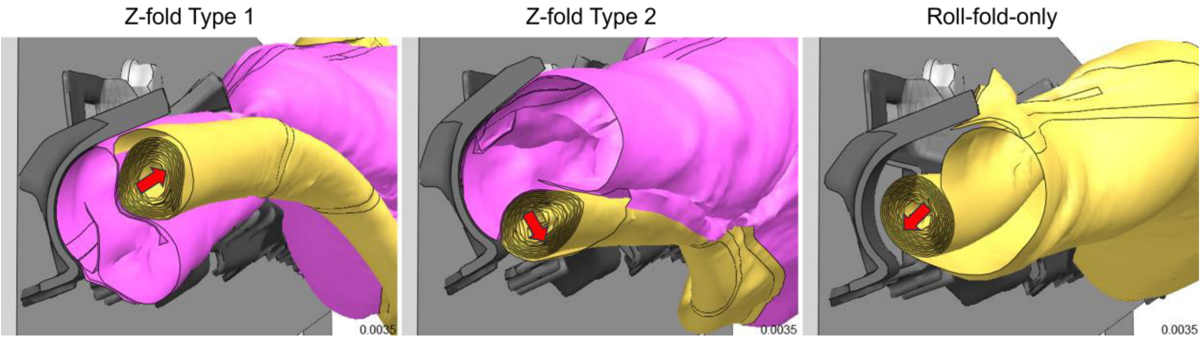

Fig.12: Comparison of deployment behaviour at 3.5 milliseconds for different folding types

Figure 13 shows a cross-sectional view of airbag deployment at 5 milliseconds. The section was rendered with a width of 10 mm to visualize the pressure distribution of CPG particles. For the Roll-fold-only pattern, the roll-folded section is in contact with the guide, restricting its movement and slowing deployment. Even as inflator gas enters, the roll-folded section remains pressed against the guide, so the airbag volume stays relatively small at 4.8 liters and the internal pressure is the highest among the patterns. In contrast, for Z-fold Types 1 and 2, the roll-folded section does not contact the guide, so deployment is faster and the airbag expands to a larger volume, 5.7 liters for Type 1 and 6.7 liters for Type 2. As inflator gas enters, the roll-folded section can move freely toward the cabin side or downward, allowing efficient expansion. This rapid expansion and increased volume result in lower internal pressure compared to the Roll-fold-only pattern. These results demonstrate that the folding pattern and its interaction with the guide significantly affect both deployment speed and pressure distribution inside the airbag.

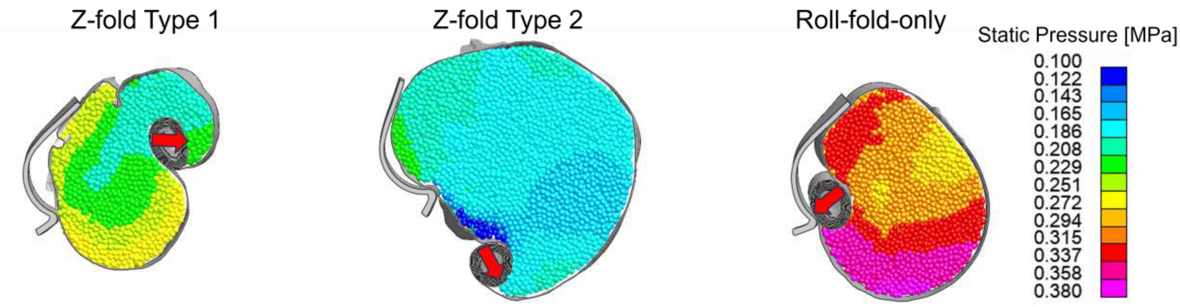

Fig.13: Comparison of pressure distribution at 5 milliseconds for different folding types

Figure 14 illustrates the airbag deployment behavior at 8 milliseconds. At this stage, the roll-folded section is expanding in all folding patterns. Observing the position of the roll-folded sections, Z-fold Type 1 has shifted toward the cabin side (right side of the image), while Z-fold Type 2 has moved slightly downward. In the Roll-fold-only case, the roll-folded section has detached from the guide and moved almost directly downward. Additionally, when comparing the deployment speed at this cross-sectional location, Z-fold Type 1 and Type 2 exhibited similar performance. The Roll-fold-only configuration showed the slowest deployment, likely due to prior contact between the roll-folded section and the guide, which impeded its movement.

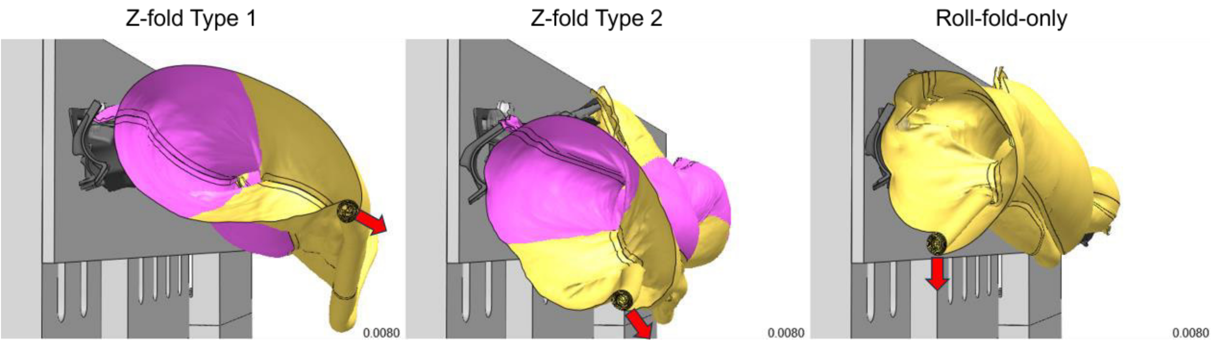

Fig.14: Comparison of deployment behaviour at 8 milliseconds for different folding types

Figure 15 provides an overview of the deployment behaviour at 20 milliseconds. In the Z-fold Type 1 and Type 2 cases, the roll-folded sections unfolded and the airbag as a whole was almost fully deployed. For Type 1, the results show that the airbag continued to move substantially towards the cabin side during deployment. In contrast, in the case with Roll-fold-only, the rear roll-folded section moved upwards, resulting in incomplete deployment. Although such behaviour would not occur in reality due to the presence of the inner panel of the roof side rail and the roof itself, these findings suggest that the Z-fold plays an important role in pushing the roll-folded section towards the cabin side.

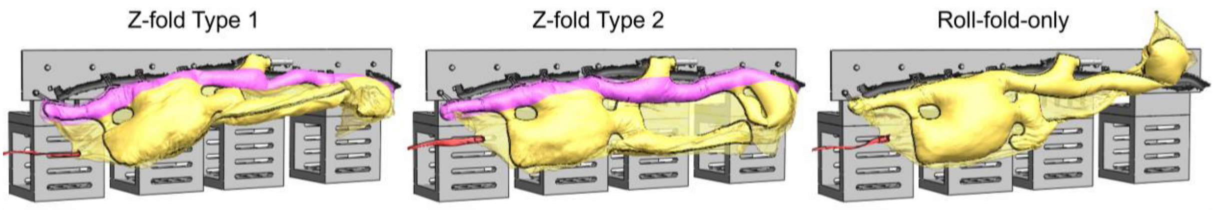

Fig.15: Comparison of deployment behaviour at 20 milliseconds for different folding types

8 Summary

In this study, multiple folding patterns were designed using the simulation-based folding tool JFOLD, based on an analysis model that had been validated against physical tests, in order to evaluate the influence of curtain airbag folding configurations on deployment behaviour. Deployment simulations were conducted using **`*AIRBAG_CPG`**, a newly implemented gas dynamics solver in Ansys LS-DYNA, and the results were compared in terms of deployment speed, direction and pressure distribution. The results confirmed that the presence and placement of Z-folds significantly affect the initial deployment behaviour. In particular, the Z-fold was shown to have a clear influence on the deployment direction by pushing the roll-folded section either toward the cabin side or toward the guide side. Compared to the conventional CPM solver, **`*AIRBAG_CPG`** demonstrated superior accuracy in reproducing gas flow through long and narrow channels, indicating its effectiveness for analysing curtain airbag deployment. From the perspective of computational cost, a hybrid approach that appropriately combines the advantages of CPM and CPG is considered the most practical for industry use.
Future work will involve expanding the study to include a wider variety of folding patterns and installation conditions, as well as further validation through comparison with physical tests, with the aim of improving the accuracy of CAE-based folding design and deployment prediction.

9 Literature

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