

Side Crash Pressure Sensor Prediction for Unitized Vehicles: An ALE Approach

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ABSTRACT

With a goal to help develop pressure sensor calibration and deployment algorithms using computer simulations, an Arbitrary Lagrangian Eulerian (ALE) approach was adopted in this research to predict the responses of side crash pressure sensors for unitized vehicles. For occupant protection, acceleration-based crash sensors have been used in the automotive industry to deploy restraint devices when vehicle crashes occur. With improvements in the crash sensor technology, pressure sensors that detect pressure changes in door cavities have been developed recently for vehicle crash safety applications. Instead of using acceleration (or deceleration) in the acceleration-based crash sensors, the pressure sensors utilize pressure change in a door structure to determine the deployment of restraint devices. The crash pulses recorded by the acceleration-based crash sensors usually exhibit high frequency and noisy responses. Different from those of the acceleration-based crash sensors, the data obtained from the pressure sensors exhibit lower frequency and less noisy responses. Due to its ability to discriminate crash severities and allow the restraint devices to deploy earlier, the pressure sensor technology has gained its popularity for side crash applications. The lower frequency and less noisy characteristics are also more suitable for non-linear finite element codes to predict.

Fifteen different benchmark problems were designed and tested in the first stage of this research to investigate the responses of pressure sensors in different impact conditions and the capabilities of the ALE method in the predictions of different pressure sensor responses. The fifteen benchmark problems were divided into three groups to examine the capabilities of the ALE method in detail. Different structures, gases, hole locations, sensor locations, hole sizes, impact speeds, and impactors, were chosen in the fifteen benchmark problems so that the sensitivity of the pressure responses to different factors could be obtained and understood. Computer simulations conducted by employing the ALE method for all fifteen benchmark problems were compared to their corresponding theoretical solutions or test data. The correlations between the tests and the computer simulations were found to be reasonable as reported in a paper published previously.

The research was advanced into its final stage, full vehicle tests, after the positive results obtained from the benchmark study. The full vehicle study included two major vehicle architectures, body-on-frame and unitized, that are commonly used to design vehicles in the automotive industry. This paper focuses on the unitized vehicles. A total of thirteen tests, including different body styles, powertrains, drivetrains, test modes, and impact speeds, were investigated.

A simulation methodology was developed in this study to correlate the structural responses and to predict the pressure sensor responses for unitized vehicles. The results obtained from the developed methodology using the ALE simulations are compared to those obtained from the corresponding tests. In the full vehicle study, low speed impact conditions were found to be more challenging to predict compared to those of the high speed impact conditions. This is because the pressure responses for the low speed impacts are usually much weaker than those of the high speed impacts. The numerical errors obtained from the simulations become more significant when the magnitudes of the pressure responses are low. The numerical errors induced by the coupling of Lagrangian and Eulerian calculation need to be distinguished and ignored (or filtered) when processing the pressure information. The slopes, peak values, and overall shapes of the predicted pressure responses correlate reasonably with most of the full vehicle tests selected. The correlations of the pre-peak responses are better than those of the post-peak responses which involve air leakage. The oblique pole, IIHS MDB, and FMVSS 214 MDB test modes create distinct door deformations and pressure responses which can be predicted by the computer simulations reasonably. Sensor engineers analyzed the results obtained from a FMVSS 214 simulation and confirmed that replacing the test data with the predicted results would result in the same deployment algorithm.

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INTRODUCTION

In conjunction with inflatable restraint devices, such as side airbags, curtain airbags, seatbelt pretensioners, and inflatable seatbelts, acceleration-based (also called G-based) crash sensors have been used in the automotive industry extensively for occupant protection. The data obtained from the G-based crash sensors in different impact conditions are analyzed by sensor engineers to develop deployment algorithms for restraint devices. The data recorded by the acceleration-based crash sensors usually has high frequency and noisy characteristics as a result of the crush and natural resonances of structural components. Therefore, it has been challenging to predict the responses of acceleration-based crash sensors by using computer simulations especially those installed in crush zones. The development of restraint deployment algorithms for vehicles with acceleration-based sensors mostly rely on physical tests.

Pressure sensors that detect dynamic pressure changes in door cavities have been developed recently for side crash applications. The side crash pressure sensors measure dynamic pressure change when a side door is deformed in the event of a side crash. The responses of the pressure sensors are different from those of the acceleration-based crash sensors. The data recorded from the side crash pressure sensors usually exhibits lower frequency and less noisy responses. In addition, the technology enables earlier detection of crash severity and allows earlier deployment decision-making which are greatly needed for side crash applications. The lower frequency and less noisy responses are also more suitable for non-linear finite element codes to predict.

Based on the available CFD (Computational Fluid Dynamics) methods, the UP (Uniform Pressure) method has been used extensively to simplify the simulation of structure-fluid interaction (SFI) problems. The UP, also called CV (Control Volume) method was developed in the 1980s by Wang and Nefske [1, 2] to approximate the time-dependent behavior of the interior pressure of an airbag. In the UP method, there is no discretization of the fluid (or gas) field. The inflating gas is modeled by two inflow factors including mass flow rate and temperature time history which usually can be obtained through tank tests. Assuming an ideal gas law and an adiabatic process, the fundamental concept of this method is based on scalar thermodynamic equations. Due to its simplicity, the computation time is extremely low and the result is robust but the local fluid effects cannot be obtained. As a result, the method is usually used to predict the global behavior of a dummy or an occupant interacting with fully deployed (in-position) side airbags or curtain airbags. The UP method also has been adopted extensively by crash safety engineers to simplify the modeling of tires and fuel tanks. In the case of OOP (out-of-position), where the dummy or occupant contacts the airbag in an earlier stage of the deployment process, more accurate CFD methods will be required to predict the local response in the transient stage.

The ALE method is one of the most advanced approaches available to solve structure-fluid interaction problems. Hughes et al. [3] developed the ALE description in the early 1980s to solve free surface flows for incompressible viscous fluids. The Lagrangian-Eulerian description and general kinematics theory developed by Hughes et al. [3] have served as the foundation of the ALE method. The Lagrangian approach, coordinate system moving with materials, is usually adopted to describe structural problems due to the relatively smaller movement of the materials. For fluid flow problems, where the materials (fluids or gases) exhibit relatively larger movements, the Eulerian system with coordinates fixed in space will be needed to describe the materials' motions mathematically. Developed for structure-fluid interaction problems, the ALE formulation allows an arbitrary Lagrangian and Eulerian coordinate system to be used to describe the materials. In the ALE calculation, discretization of both the structures and the fluid (gas) volumes is needed. Different from the UP method, the local responses of the gases or fluids can be predicted in the ALE calculation. As a result, the ALE method has been considered to be one of the most accurate methods for applications involving detailed predictions of structure-fluid interactions. More detailed information on the ALE theory and computation schemes can be found in Hughes et al. [3], Benson [4], Olovsson [5], and Hirth et al. [6].

The ALE method has been used extensively to model the fuel sloshing of fuel tanks under high speed impact conditions. Ma and Usman [7] used the ALE method available in LS-DYNA to design a baffle during the development of a fuel tank. Tang et al. [8] adopted the ALE calculation to study the sloshing of fuel and ballooning of deformable fuel tanks in high speed impact conditions. Similarly, Craig et al. [9] employed the ALE method to predict fuel sloshing and tank deformation with considerations of blow molding simulations of thermoplastic tanks and tank strap pre-tension.

The ALE method is also a good candidate for other applications such as bird strike, bulk metal forming, air blast, gun launch, and other structure-fluid interaction scenarios. Souli and Olovsson [10, 11] developed a new Lagrangian-Eulerian coupling algorithm to enhance the application of the ALE method in the areas of bird strike and die forging. More applications of the ALE formulation to the bird strike problems can also be found in McCallum and Constantinou [12] and Anghileri et al. [13]. Many bulk metal forming processes, including extrusion, cutting, and punching, can be simulated by employing the ALE method as illustrated by Gadala and Wang [14] and Movahhedy et al. [15]. Slavik [16] implemented a coupling method in LS-DYNA to allow empirical explosive blast loads to be applied to air domains treated with the ALE formulation. Lapoujade et al. [17] worked with LSTC to implement a new mapping technique for the air blast problems that were simulated by using the ALE method. Tabiei and Chowdhury [18] illustrated the use

of the ALE method to predict the dynamics behavior of a generic gun launch.

Many researchers have made attempts to adopt the ALE method for airbag deployment simulations, especially the OOP applications where the local response of transient stage cannot be predicted by using the UP method. Olovsson [5], Marklund [19], Markland and Nilsson [20], and Fokin et al. [21] are among the earlier researchers to demonstrate how to employ the ALE formulation to model inflators and airbag deployments. The deployments of airbags using the ALE formulation were found to be more accurate than those of the UP method. Thereafter, Haufe and Weimar [22], and Lian [23] have employed the ALE calculation to simulate the transient deployments of airbags with a focus on the OOP test condition. Recently, the ALE method was adopted by Feng and Coleman [24] to simulate the deployments of side curtain airbags through vehicle interior trims.

The predictions of the side crash pressure sensor responses involve the modeling of a door structure and the air inside the door cavity. Physically, it is very similar to the modeling of fuel sloshing and/or airbag deployments. Based on the review conducted above, the ALE method is one of the best candidates for such applications. Machens and Wessels [25] made the first attempt in 2007 to investigate the pressure changes inside a door under side impact conditions by adopting the ALE calculation. As expected, the door responses with air consideration inside a door cavity were found to be different from those without air consideration. It was also reported that the use of the ALE formulation to model the air allowed reasonable predictions of air pressure inside a door. Recently, Lin and Jerinsky [26] adopted both the UP and the ALE methods to predict the side door pressure responses with a focus on full vehicle side impact conditions. They concluded that the ALE method, although requiring more computation time, is able to predict accurate pressure responses in the early phase of the impact. The UP method can predict only the average door pressure. It was also reported that both the ALE method and the UP method can be used to predict the pressure responses needed for sensor algorithm developments.

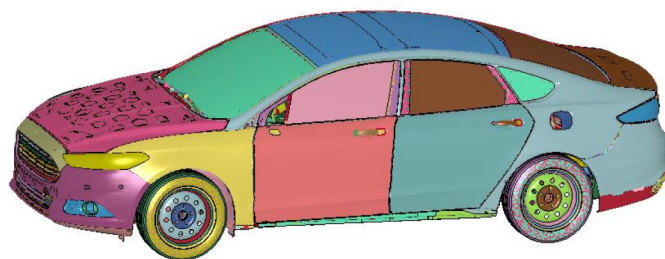
To investigate the responses of pressure sensors in different impact conditions and the capabilities of the ALE method in the prediction of different pressure sensor responses, fifteen different benchmark problems were designed and tested in the first stage of this research [27, 28, 29]. The fifteen benchmark problems were divided into three groups so that the capabilities of the ALE method can be examined in detail. The first group of benchmark problems included a rectangular steel container with one side being compressed while all other sides were fixed to simulate a piston compression condition. The solutions of the designed piston compression problems could be derived theoretically since the compression process was assumed to be isentropic. Two different gases were simulated in the first group of benchmark tests to compare with those of the theoretical solutions. The second group of benchmark problems, a series

of eight, involved a rigid impactor or a deformable barrier hitting a rectangular steel box with and without a hole. Different hole locations and impact speeds were also considered as variable in the second group of benchmark problems so that the sensitivity of pressure responses to the hole size, hole location, and impact speed can be obtained and understood. The third group of benchmark problems, a series of five, involved a rigid impactor or a deformable barrier hitting a vehicle side door with different openings. Similar to the second set of the benchmark tests; different openings and impact speeds were chosen to create different crash severities. The results of computer simulations conducted by employing the ALE method for all the fifteen benchmark problems were compared to their corresponding theoretical solutions or test data. Reasonable correlations had been found between the tests and the computer simulations from thirteen of the fifteen benchmark problems and the results have been documented and published in detail [27, 28, 29].

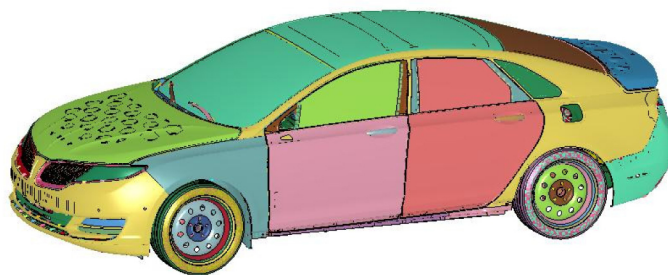
The research is advanced into its final stage, full vehicle study, with the confidence obtained from the benchmark study. Both body-on-frame [30] and unitized vehicles are included in the full vehicle study. This paper focuses on the unitized vehicles. Thirteen tests, including combination of different body styles, powertrains, drivetrains, test modes, and impact speeds, were investigated. A simulation methodology was developed in this study to correlate the structural responses and to predict the pressure sensor responses for unitized vehicle side impact tests. The developed methodology employing the ALE method and the results obtained from the developed methodology are documented and discussed below in detail.

FULL VEHICLE MODELS

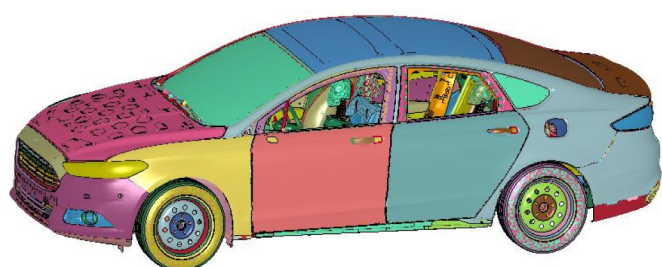
Thirteen unitized vehicle tests were investigated in this study. The thirteen tests obtained from two different body styles, vehicle B and vehicle C, are shown in [Figure 1 \(a and b\)](#). The finite element model created for vehicle B has 2,802,411 nodes, 2,489,496 shells, 856,540 solids, and 99,900 beams. The vehicle C model contains 2,663,605 nodes, 2,399,069 shells, 857,738 solids, and 92,190 beams. Two drivetrains, a 6 speed transmission and a continuously variable transmission (CVT), and five engines, 1.6L I4 EcoBoost, 2.0L I4 EcoBoost, 2.0L HEV, 2.5L iVCT, and 3.7L V6, were included in the full vehicle study. Three side impact modes, oblique side pole, IIHS MDB, and FMVSS 214 MDB, were investigated in this study. The finite element models of SID-IIIs and ES-2re dummies, required in different side impact simulations, were included in the full vehicle models, as shown in [Figure 2](#). Illustrated in [Figure 3](#), the oblique side pole model (127 mm radius) has 24,080 nodes and 24,000 shells while the IIHS MDB model (mass 1500 kg, 379 mm above ground, 759 mm height, 1676 mm width, 90 degree) has 142,793 nodes, 38,501 shells, 94,048 solids, and 22 beams. The FMVSS 214 MDB (mass 1368 kg, 279 mm



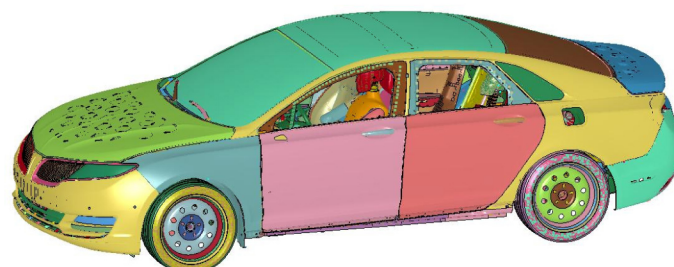
(a) Vehicle B.



(b) Vehicle C

Figure 1. Full vehicle finite element models for the two body styles.

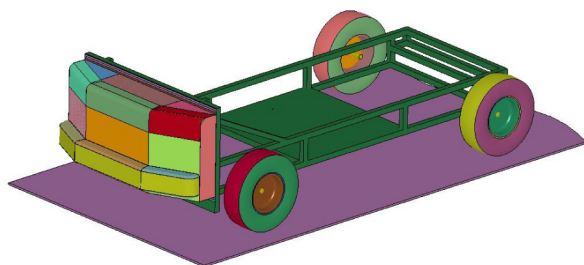
(a) Vehicle B with two SID-IIs dummy models.



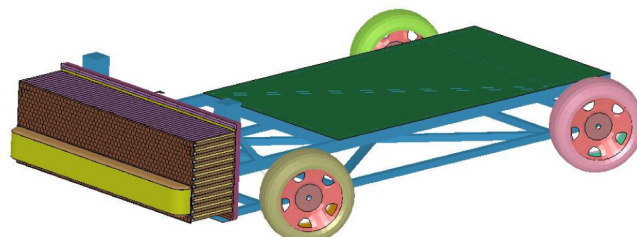
(b) Vehicle C with ES-2re and SID-IIs dummy models.

Figure 2. Finite element dummy models used in the full vehicle simulations.

(a) Oblique Pole.



(b) IIHS MDB model.



(c) FMVSS 214 MDB model.

Figure 3. Finite element models of striking objects for side impacts.

above ground, 559 mm height, 1676 mm width, 27 degree crab angle) was modeled with 238,130 nodes, 487,428 shells, 108,788 solids, and 20 beams. As shown in [Figure 3b](#) and [3c](#), solid elements were used to model the honeycomb materials (bumper and main blocks) in the IIHS MDB while shell elements were used to model the FMVSS 214 MDB main honeycomb block.

VEHICLE STRUCTURE RESPONSES

The door deformation and the structural responses surrounding the door affect the prediction of the door pressure as found in the previous benchmark studies [[27](#), [28](#), and [29](#)]. Due to different side impact conditions, a door can deform differently in different test modes. Relatively speaking, the oblique pole tests tend to create a more concentrated door deformation in vertical direction while the IIHS side and the FMVSS 214/LINCAP test modes produce a

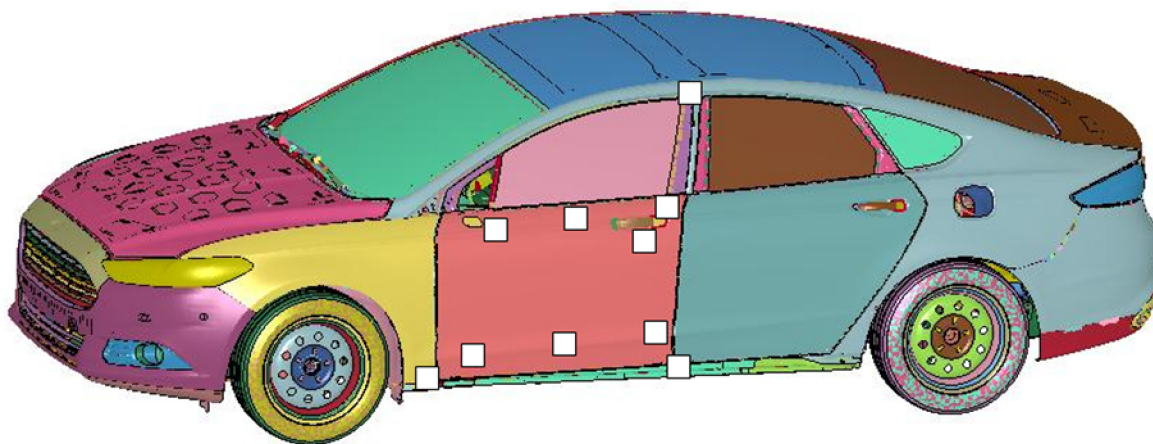


Figure 4. Monitored locations (white squares) at door and surrounding structures.

wider spread door deformation in horizontal direction. The door also deforms more severely in high speed impact conditions than in low speed impact conditions. As a result, it is essential to have accurate structural responses for the entire door and at the areas surrounding the door if the full vehicles are to be used to predict the door pressure responses for different impact conditions. In this study, an approach is proposed to ensure that the quality of an unitized vehicle model would be sufficient for pressure sensor predictions. Ten locations, shown in [Figure 4](#), on the door and surrounding the door are proposed to be monitored and correlated prior to pressure response predictions. The ten locations include Rocker@A-Pillar, Rocker@B-Pillar, Door@Handle, Door@Roof, Door@Beltline (front), Door@Beltline (mid), Door@Beltline (rear), Door Bottom (front), Door Bottom (mid), and Door Bottom (rear). In addition, the door deformation is directly affected by the interaction between the vehicle and the MDB. As a result, the velocities between the door and the MDB C.G. also need to be compared and correlated to assure that the interaction between the vehicle and the MDB is accurate. The full vehicle models can be adopted for pressure sensor predictions once the above mentioned responses are correlated reasonably.

Based on the approach mentioned above, the vehicle structural responses obtained from this study are shown in [Figure 5](#) for illustration purposes. The correlation of the structure responses has led to the prediction of door pressure response that will be discussed later. Since an objective judgment of correlation quality between a simulation and a test is rather difficult, the documented results can be utilized as a reference point for future implementations. Due to lack of test data at some locations, the comparison between the test and the simulation is made only for the locations that were available, as shown in [Figures 5a to 5e](#). From the pressure sensor point of view, only the responses for the first 15 ms are needed to develop the deployment algorithms for a restraint system because the deployment time for a restraint

system usually ranges from 4 ms to 13 ms depending on impact modes and vehicle designs. To ensure the vehicle model is as robust as possible, the comparisons of structural responses are made for the entire side impact duration in this study. Correlated vehicle models are the foundation to accurate predictions of door pressure responses.

LAGRANGIAN MODEL: DOOR STRUCTURE

The door is the most critical component in the prediction of door pressure responses. The finite element door models created for the side crash pressure sensor predictions are shown in [Figures 6](#) and [7](#) for vehicle B and vehicle C, respectively. Attention needs to be paid to the modeling of door components. In this study, almost all internal and external components are included in the door model except for some cables and electric wires. The models of external door components, such as door outer, door frame, side glass, door handle, interior trims, door latch, arm rest, map pocket, speaker, and door hem, are shown in [Figures 6a, 6b, 7a, and 7b](#). The different internal components can affect the propagation of pressure (shock) waves in addition to their contributions to local structure stiffness. Internal door components such as door beams, latch and window mechanisms, side glass guides, beltline reinforcements, motors, connection brackets, door inner, and so on can be found in [Figures 6c and 7c](#). One of the most important door components in the prediction of pressure responses is the weather shields which can be seen in [Figures 6d and 7d](#).

EULERIAN MODEL: AIR

Eulerian elements were created to represent the air inside and outside the door. The door dimensions of vehicle C are slightly larger than those of the vehicle B. The dimensions of the Eulerian domain were created based on vehicle C so that it can be used for both vehicles. As shown in [Figures 8 and 9](#), the final dimensions of the Eulerian domain are $1300 \times 460 \times 1220 \text{ mm}^3$ after some adjustments in the

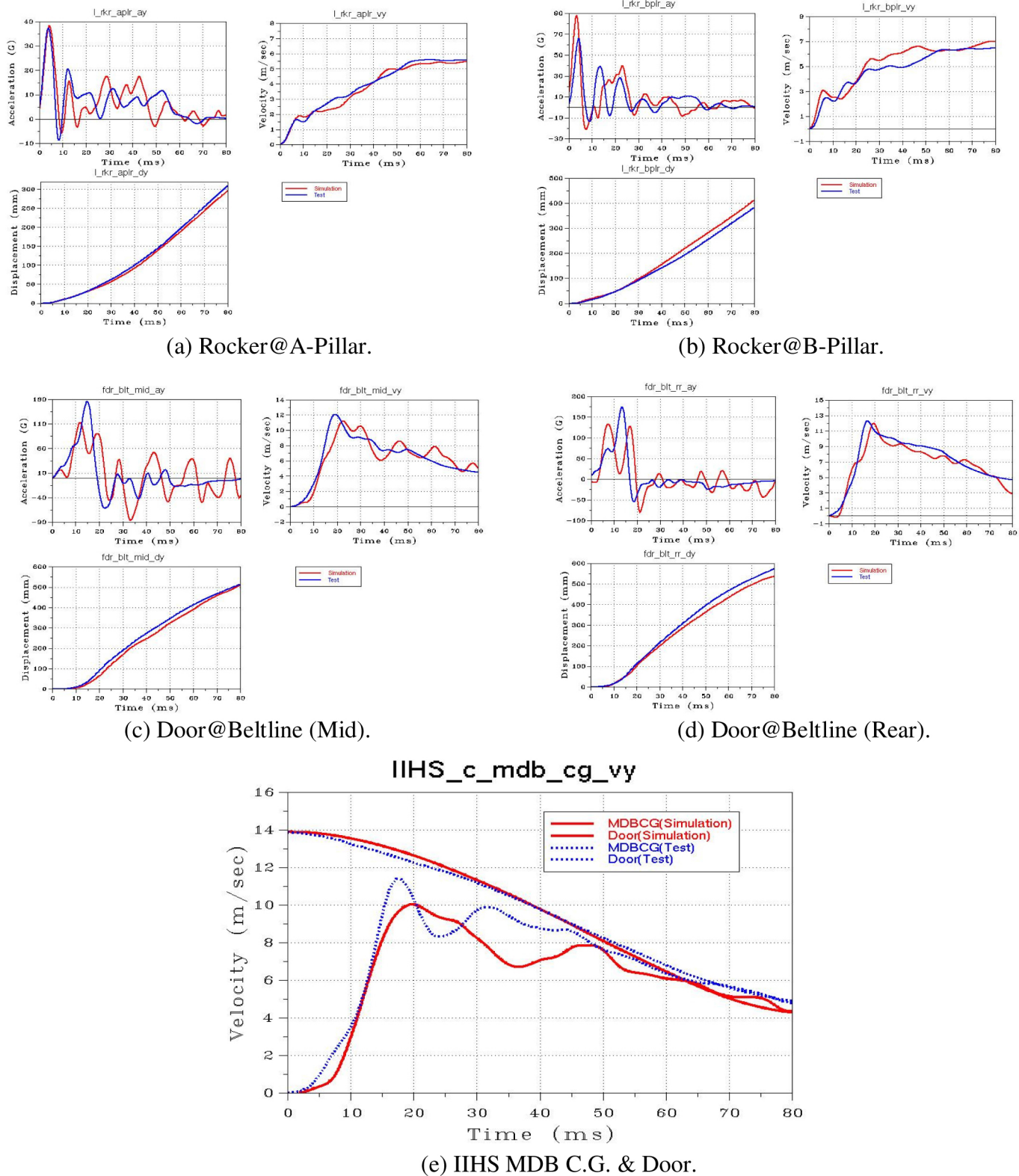


Figure 5. Responses of the door and the MDB obtained from tests and simulations.

beginning of the study. The air inside the door can be seen in Figures 8a and 9a for vehicle B and vehicle C, respectively. Several Eulerian meshes were created in the study to cover

the possible leakage areas of the door and to cover the door movements in all different side impact modes. Figures 10a and 10b illustrate two of the meshes that were created

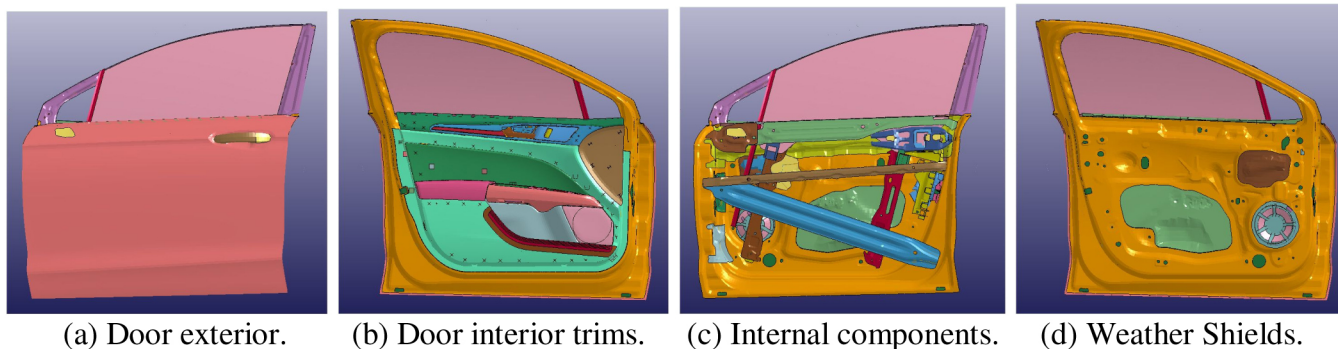


Figure 6. Door structures (Lagrangian) for vehicle B.

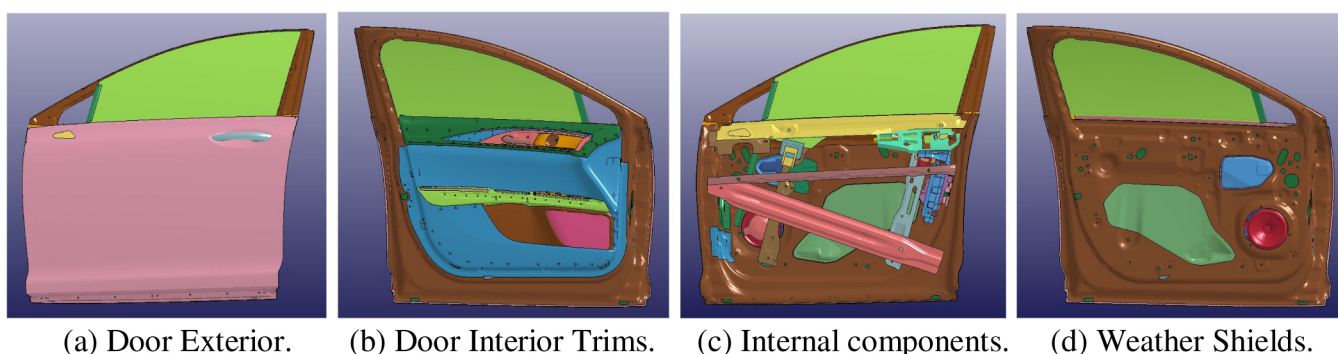


Figure 7. Door structures (Lagrangian) for vehicle C.

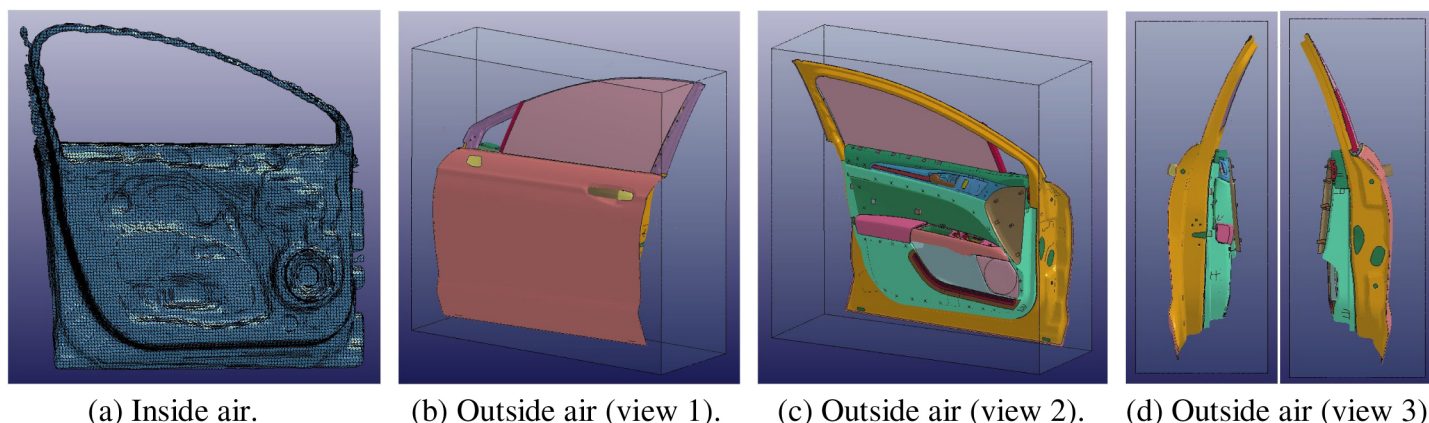


Figure 8. Eulerian domain defined for vehicle B with the air inside and outside the door.

through the study. Excessive Eulerian elements will not allow the simulations to be conducted. To balance the numerical calculations and the coverage of door movements, the optimized mesh, shown in Figure 10b, was chosen for all simulations. The size of the Eulerian element is $10.0 \times 2.0 \times 10.0 \text{ mm}^3$ in the refined area and $10.0 \times 5.0 \times 10.0 \text{ mm}^3$ in the coarse areas. The entire Eulerian mesh has 2,207,481 nodes and 2,125,240 solid elements.

Additional door components were also created for the ALE calculations and for the air leakage predictions, as shown in Figures 11a and 11b for vehicle B and vehicle C, respectively. For illustration purposes, the domain of the Eulerian mesh with respect to the Lagrangian mesh is shown in Figure 12a and 12b for vehicle B and vehicle C, respectively. A “moving mesh” option was adopted with a reference coordinate defined on hinge pillar and B-pillar so that the Eulerian mesh can move with the door. The “moving

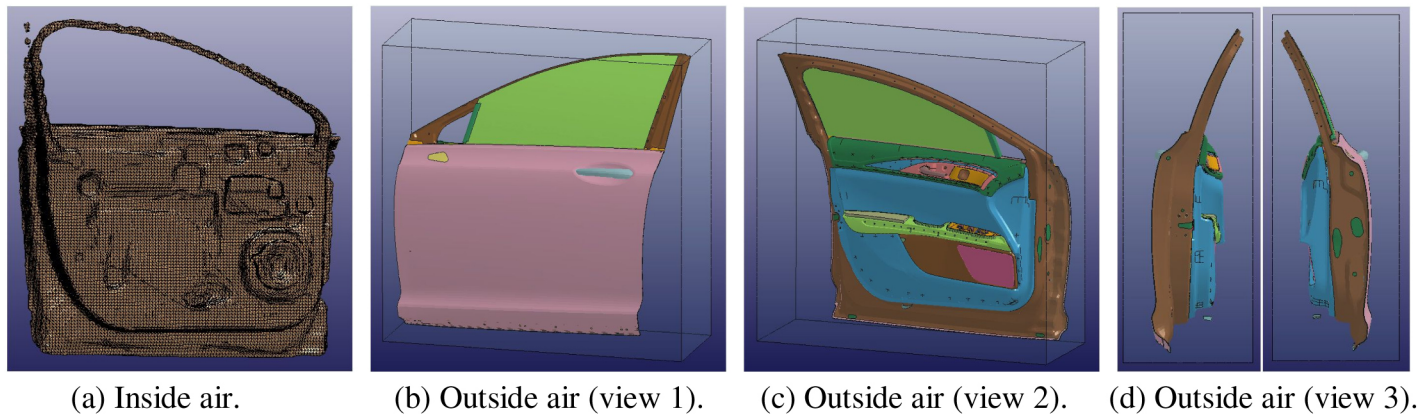


Figure 9. Eulerian domain defined for vehicle C with the air inside and outside the door.

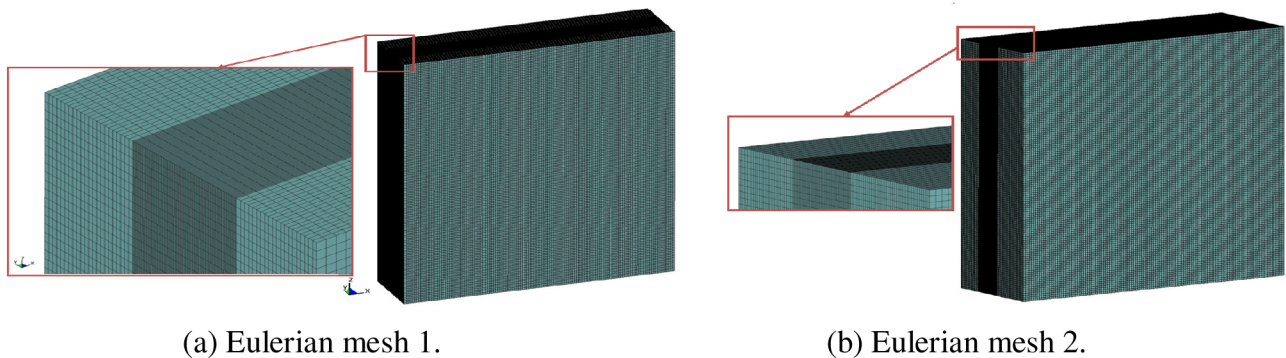
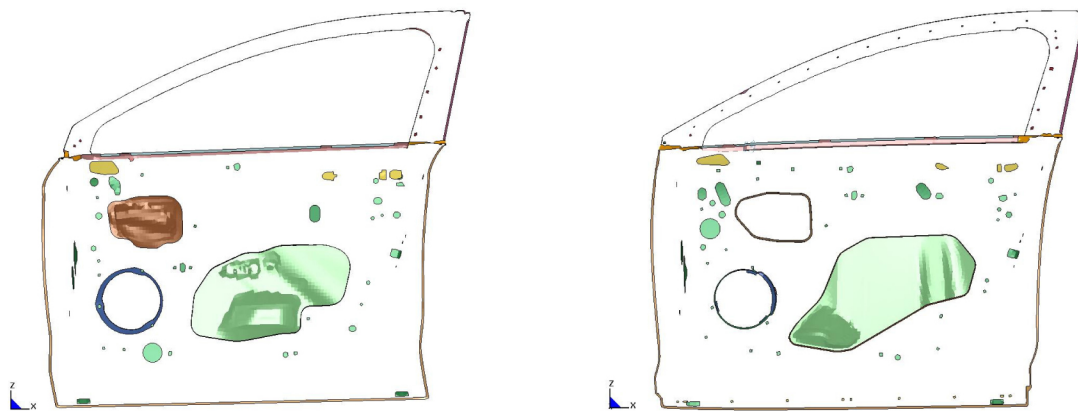


Figure 10. Eulerian meshes created for ALE calculations.



(a) Additional Lagrangian components in vehicle B. (b) Additional Lagrangian component in vehicle C.

Figure 11. Additional Lagrangian components created for ALE calculations.

mesh” option allows the Eulerian domain and computational time to be minimized. Otherwise, the possible movement of the door would need to be estimated in advance and a larger Eulerian domain would need to be created to cover the door's movements for different side impact conditions. With the

optimized Eulerian mesh, the total element number is around 6.5 million for a typical side impact simulation, including the Lagrangian meshes from a full vehicle, a side airbag, a curtain airbag, two floors, two dummies, and a side MDB as well as the solid elements needed for the Eulerian mesh.