

Side Crash Pressure Sensor Prediction for Body-on-Frame Vehicles: An ALE Approach

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ABSTRACT

In an attempt to assist pressure sensor algorithm and calibration development using computer simulations, an Arbitrary Lagrangian Eulerian (ALE) approach was adopted in this study to predict the responses of side crash pressure sensors for body-on-frame vehicles. Acceleration based, also called G-based, crash sensors have been used extensively to deploy restraint devices, such as airbags, curtain airbags, seatbelt pre-tensioners, and inflatable seatbelts, in vehicle crashes. With advancements in crash sensor technologies, pressure sensors that measure pressure changes in vehicle side doors have been developed recently and their applications in vehicle crash safety are increasing. The pressure sensors are able to detect and record the dynamic pressure change when the volume of a vehicle door changes as a result of a crash. Due to the nature of pressure change, data obtained from the pressure sensors exhibits lower frequency and less noise in the responses which are significantly different from those of the acceleration-based crash sensors. This technology is very suitable for side crash applications due to its ability to discriminate crash severities and deploy restraint devices earlier in the event. The lower frequency and less noise in the responses are also more suitable for non-linear finite element codes to simulate.

To help understand the responses of pressure sensors and the capabilities of the ALE method in the prediction of pressure sensor responses, fifteen different benchmark tests were designed and performed in previous research. The fifteen benchmark tests were divided into three groups so that the capabilities of the ALE method could be examined in detail. The first group of benchmark tests included a rectangular steel container with one side being compressed while all other sides were fixed to simulate a piston compression condition. Two different gases were tested in the first group of benchmark tests. Solutions for the first group of benchmark tests can be derived theoretically. The second group of benchmark tests, a series of eight, involved a rigid impactor or a deformable barrier hitting a rectangular steel box with and without a hole. In addition, different speeds were chosen in the second group of component tests to obtain their corresponding responses. The third group of benchmark tests, a series of five, involved a rigid impactor or a deformable barrier hitting a vehicle side door with different openings. Similar to the second group of benchmark tests, different speeds were chosen to create different crash severities. Computer simulations conducted employing the ALE method for all fifteen benchmark tests were compared to their corresponding theoretical solutions or test data. Reasonable correlations had been found between the benchmark tests and the computer simulations as presented and discussed in a previous paper.

The success of the benchmark study allowed the advancement of the research into its final stage, full vehicle tests. The full vehicle tests contained both body-on-frame and unitized vehicles which are the two main vehicle architectures used in the automotive industry. This paper focused on the body-on-frame vehicles with fifteen tests, including a combination of different body styles, powertrains, drive-trains, wheel bases, test modes, and impact speeds, being investigated. In this study, an approach was developed to correlate the structural responses and to predict the pressure sensor responses for body-on-frame vehicles. The results obtained from the developed method are compared to those obtained from tests. Contrary to common thoughts, it was found that the pressure responses of the low speed test conditions are more challenging to predict than those of the high speed test conditions. This is because the pressure responses for the low speed test conditions are usually very weak. The errors obtained from the numerical simulations become predominant when the magnitudes of the pressure responses are small. The numerical fluctuations induced by the coupling of Lagrangian and Eulerian calculation need to be distinguished and ignored (or filtered) when processing the pressure information. Overall, the slopes, peak values, and shapes of the predicted pressure responses correlate reasonably well with those of the fifteen full vehicle tests selected. The pre-peak responses seem to correlate better to those of the tests than the post-peak responses which involve air leakage. The door pressure changes due to the impacts of oblique pole, IIHS MDB, and FMVSS 214 MDB, can be captured reasonably by the computer simulations.

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INTRODUCTION

Acceleration-based crash sensors have been used in the automotive industry in conjunction with pyrotechnic restraint devices such as side airbags, curtain airbags, seatbelt pretensioners, and inflatable seatbelts for occupant protection. The data obtained from the acceleration-based crash sensors in different impact conditions are analyzed to develop deployment algorithms for the restraint devices. Due to the crush and folding of structural components in combination with the components' natural resonances, the data recorded by the acceleration-based crash sensors usually exhibit high frequency and noisy responses. As a result, it is very challenging to predict the responses of acceleration-based crash sensors by using computer simulations, especially those installed in crush zones. Historically, sensor engineers primarily have relied on physical testing to develop restraint deployment algorithms for vehicles equipped with acceleration-based sensors.

With the advancement of crash sensor technologies, pressure sensors have been developed recently and are being gradually implemented for side impact applications. The pressure sensors detect dynamic pressure change as soon as the door volume starts to change in the event of a side crash. Due to the nature of pressure change, the data recorded from the side crash pressure sensors exhibits lower frequency and less noise in the responses compared to those of the acceleration-based crash sensors. This technology provides the benefits of earlier detection of crash severity and quicker deployment decision-making time that are needed for side impact applications. The lower frequency and less noise in the responses are more favorable for non-linear finite element codes to simulate.

Several available CFD (Computational Fluid Dynamics) methods, including UP (Uniform Pressure), ALE and CPM (Corpuscular Particle Method), are good candidates for prediction of pressure responses. The UP 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, discretization of fluid fields is not needed. Without discretization of the fluid fields, the modeling effort is significantly reduced. 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. Based on scalar thermodynamic equations and with assumptions of ideal gas law and an adiabatic process, the computation time for the UP method is extremely low and the result is very robust.

However the local fluid effects cannot be obtained due to the simplification of the problem. Therefore, the method is usually used by occupant safety engineers to predict the interactions of dummies with fully deployed (in-position) airbags or curtain airbags. Crash safety engineers have

adopted the UP method to simplify the modeling of tires and fuel tanks in the past. To simulate the dynamic interaction between a dummy and an airbag in the transient phase of the airbag deployment process, such as in the case of an OOP (out-of-position) test condition, more accurate CFD methods are required.

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

Fuel sloshing in fuel tanks under high speed impact conditions is another application that the ALE method can handle very well. Ma and Usman [7] designed a baffle during the development of a fuel tank by using the ALE formulation available in LS-DYNA. Tang et al. [8] adopted the ALE calculation to simulate the sloshing of fuel and to predict the ballooning effect and stress concentration of deformable fuel tanks in high speed impact conditions. Similarly, Craig et al. [9] employed the ALE method to predict fuel tank sloshing and tank strap pre-tension with considerations of blow molding processes of thermoplastic tanks and assembly processes of fuel tank straps.

Simulations such as bird strike, bulk metal forming, air blast, gun launch, and other similar scenarios can also be conducted using the ALE method. To enhance the ALE method in the applications of bird strike and die forging, Souli and Olovsson [10, 11] developed a new Lagrangian-Eulerian coupling algorithm. Additional applications of the ALE method to the bird strike problems can be found in McCallum and Constantinou [12] and Anghileri et al. [13]. Several 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] developed a coupling method in LS-DYNA to allow empirical explosive blast loads to be applied to air domains treated with the ALE formulation. Working with LSTC, Lapoujade et al. [17] implemented a new mapping technique in the ALE method for the air blast problems. Tabiei and Chowdhury [18] demonstrated the possibility to predict the dynamic behavior of a generic gun launch using the ALE method.

The ALE method also has been adopted by many researchers to conduct airbag deployment simulations, especially the OOP applications where the local response of transient stage cannot be predicted using the UP method. Olovsson [5], Marklund [19], Markland and Nilsson[20], and Fokin et al. [21] are among the earlier researchers to simulate inflators and airbag deployments by employing the ALE method. From their studies, the deployments of airbags using the ALE method were found to be more accurate than those of the UP method. Subsequently, Haufe and Weimar [22], and Lian [23] all have employed the ALE method to simulate the transient deployment of airbags in an attempt to predict the OOP test condition. In 2008, the ALE method was adopted by Feng and Coleman [24] to simulate the deployment of side curtain airbags through headliners and pillar trims.

Similar to the modeling of fuel tanks and/or airbags, the prediction of side crash pressure sensor responses involves the modeling of the door structure and the air inside and outside the door cavity. Based on the review conducted above, the ALE method can be a good candidate for such applications. By adopting the ALE method, Machens and Wessels [25] made an attempt in 2007 to investigate the pressure changes of a vehicle door undergoing different impact conditions. In the investigation, the door response with air consideration inside a door cavity was found to be different from those without air consideration. The study also indicated that using the ALE method to model the air inside a door led to more reasonable predictions of door pressure.

In 2011, Lin and Jerinsky [26] adopted both the UP and the ALE methods to predict the side door pressure responses in several full vehicle side impact conditions. Air leakage plays a critical role in the success of side door pressure prediction. In this study, two thirds of the window aperture was defined as a vent hole, while the rest of window aperture was blocked. It was concluded that the ALE method is able to predict more accurate results in the early phase of the impact, whereas the UP method can predict only the averaged door pressure. It was also reported that both the ALE and the UP methods can be used to predict the pressure responses required in the development of restraint deployment algorithms.

Recently, Tyan, McClain, Arthurs, Rupp, et al. [27, 28, and 29] designed fifteen different benchmark tests and performed simulations by employing the UP, ALE and CPM methods to understand the responses of pressure sensors and the capabilities of the three available CFD methods in the

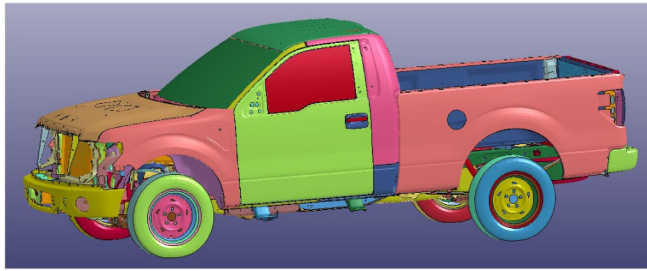
predictions of pressure sensor responses. The fifteen benchmark tests were divided into three groups so that the capabilities and limitations of the three CFD methods could be investigated carefully. The first group of benchmark problems, simulating piston compression tests, involved a rectangular steel container with one side being compressed downward while all other five sides were fixed. Two different gases were tested in the first group of benchmark tests. Theoretical solutions for the two benchmark tests could be derived since the compression process was assumed isentropic. The second group of benchmark tests, a series of eight, involved a rigid impactor or a deformable barrier hitting a rectangular steel box with and without a hole. In addition to hole size, hole location and impactor, different impact speeds were chosen in the test matrix to understand the responses of pressure to different impact conditions. The third group of benchmark tests, a series of five, involved a rigid impactor or a deformable barrier hitting a vehicle side door with different openings. Similar to the second group of benchmark tests, different impactors, openings, and impact speeds were considered in the test matrix to create different crash severities. Computer simulations conducted by employing the three CFD methods for all fifteen benchmark tests were compared to their corresponding theoretical solutions or test data. Discussions of the results between the benchmark tests and the computer simulations and comparisons of computational performances among the three CFD methods have been documented and presented in detail [27, 28, and 29].

The success of the benchmark study permitted the final stage of this research, full vehicle tests, to be conducted.

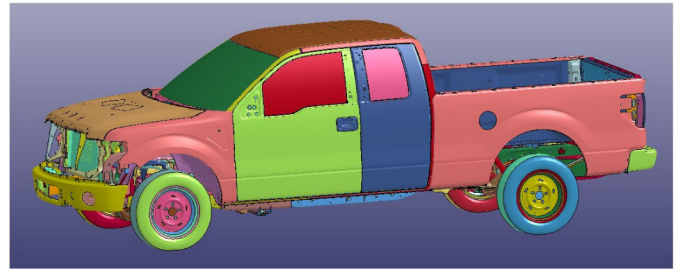
The full vehicle study contained both body-on-frame and unitized vehicles [30]. This paper documented only the body-on-frame vehicles with fifteen tests, including a combination of different body styles, powertrains, drive-trains, wheel bases, test modes, and impact speeds, being investigated. The configurations of the vehicles used in the tests and the details of the full vehicle finite element models used in this study are summarized below. Through the study, an approach was developed to correlate the structural responses and to predict the pressure sensor responses in full vehicle side impact tests. The developed approach employing the ALE method and the results obtained from the developed approach are documented and discussed in the following.

FULL VEHICLE MODELS

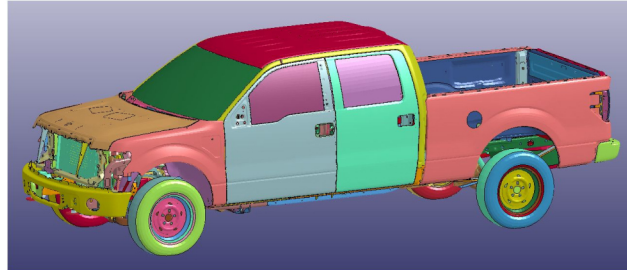
A total of fifteen full vehicle tests belonging to the same vehicle family (called “vehicle A”) were investigated in this study. The fifteen tests chosen from vehicle A had three different body styles, regular cab, super cab, and crew cab, as shown in Figure 1 (a, b, and c). The regular cab finite element model contains 961,979 nodes, 881,574 shells, 50,946 solids, and 27,921 beams. The super cab model has 1,106,981 nodes, 1,022,514 shells, 50,946 solids, and 31,748 beams. There are 1,040,875 nodes, 952,648 shells, 50,946 solids, and 30,373



(a) Regular Cab.

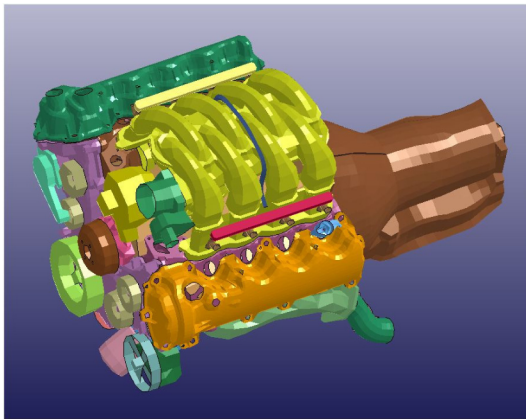


(b) Super Cab.

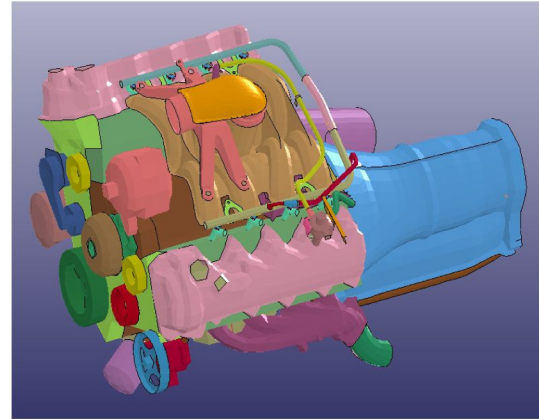


(c) Crew Cab.

Figure 1. Full vehicle finite element models for the three main body styles in vehicle A.



(a) 4.6L V8.



(b) 5.4L V8.

Figure 2. Finite element engine models used in this study.

beams in the crew cab model. Although many powertrain options were available for vehicle A, only two engines, 4.6L V8 and 5.4L V8, were included in the fifteen tests selected. The models of the two engines are illustrated in [Figure 2 \(a and b\)](#). Three major side impact test modes, oblique pole, IIHS MDB, and FMVSS 214 MDB, are all covered in this study with the finite element models of the corresponding impactors shown in [Figure 3 \(a, b, and c\)](#). 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 above ground, 559 mm height, 1676 mm width, 27 degree

crab angle) was modeled with 153,021 nodes, 27,081 shells, 113,497 solids, and 21 beams. As can be seen in [Figure 3b and 3c](#), solid elements were used to model the honeycomb materials in the IIHS and FMVSS 214 MDB models.

VEHICLE STRUCTURAL RESPONSES

The prediction of the door pressure responses depends on not only the door deformation but also the structural responses surrounding the door as indicated in previous studies [[27](#), [28](#), and [29](#)]. Therefore, the structural responses of full vehicle models, especially the door and the areas surrounding the door, need to be as accurate as possible if the

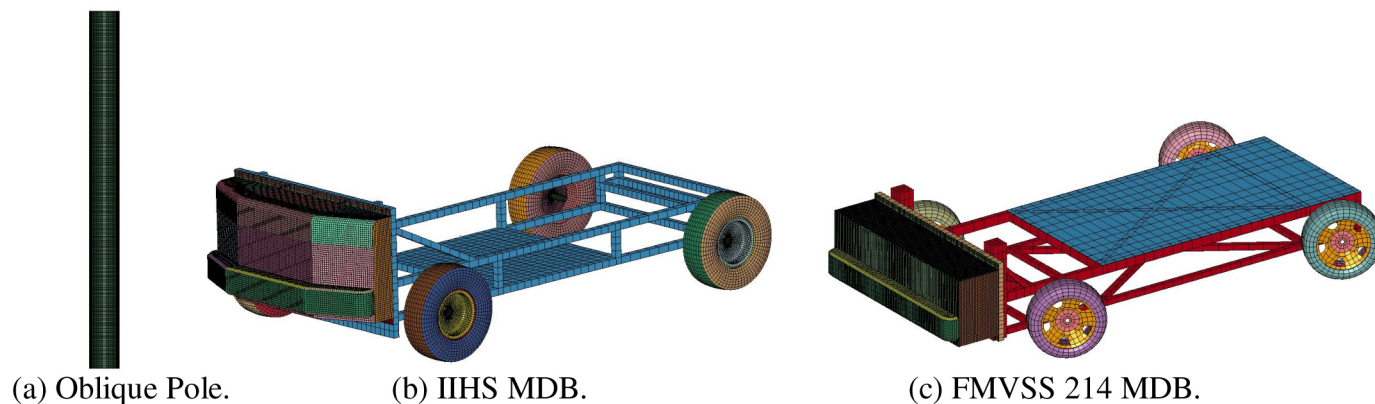


Figure 3. Finite element models of striking objects for side impacts.

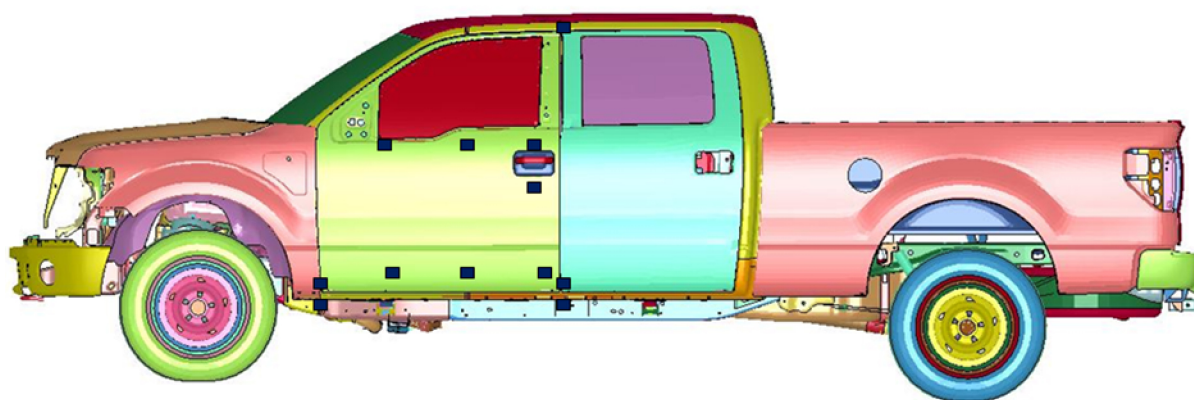
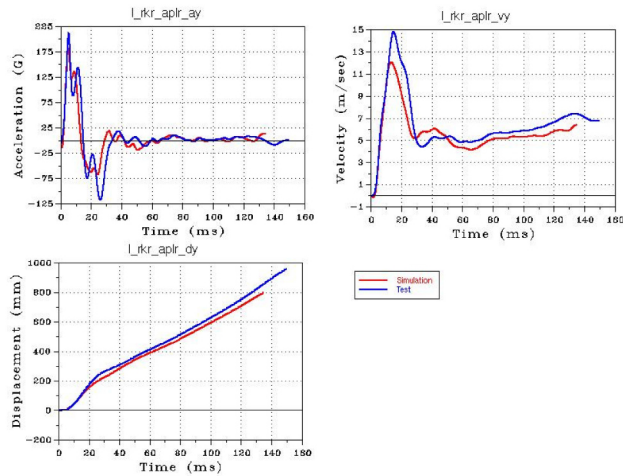


Figure 4. Monitored locations (blue squares) at door and surrounding structures.

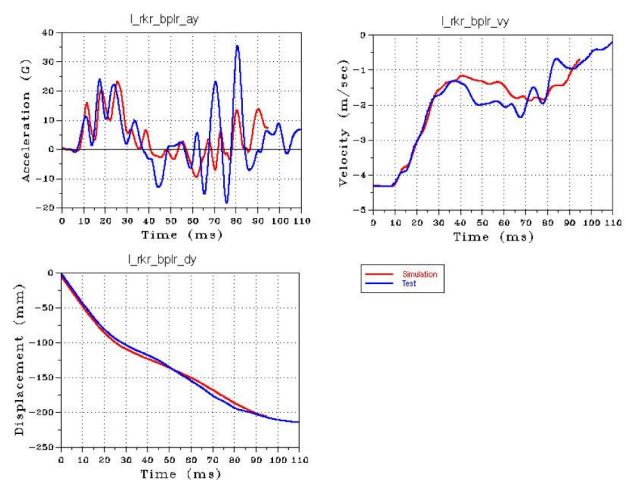
goal is to predict the door pressure responses. An approach is developed in this study to ensure a body-on-frame full vehicle model is sufficient for pressure sensor predictions. Twelve locations, shown in [Figure 4](#), on the door and surrounding the door are proposed to be monitored and correlated between tests and simulations. The twelve locations include Rocker@A-Pillar, Rocker@B-Pillar, Frame@A-pillar, Frame@B-Pillar, Door@Handle, Roof@B-Pillar, Door@Beltline (Front), Door@Beltline (Mid), Door@Beltline (Rear), Door Bottom (Front), Door Bottom (Mid), and Door Bottom (Rear). The first four locations, Rocker@A-Pillar, Rocker@B-Pillar, Frame@A-pillar, and Frame@B-Pillar, providing information regarding the vehicle's global responses and the relative motion between the cab and the frame, are already monitored routinely by crash safety engineers in regular crash tests and analyses. To provide the test data mentioned above without adding additional tests, the accelerometers for the last eight locations can be instrumented on prototype vehicles intended for vehicle certification and/or occupant injury assessment. In addition, the interaction between the vehicle and the MDB should be accurate since the interaction affects the door deformation directly. To achieve this goal, the velocities

between the MDB C.G. and door also need to be compared and correlated. Once reasonable correlations for the above mentioned responses are achieved, the full vehicle model can be used for pressure response predictions.

To illustrate the proposed approach, the structural responses correlated in this study are documented in [Figure 5](#). The documented results also serve as a reference for future implementations. Two accelerometers, Door@Beltline (Front) and Door@Beltline (Mid), were not installed in the selected tests. Due to lack of test data, the comparison between the test and simulation for the two locations are not compared. The results obtained for the remaining ten locations are shown in [Figures 5a to 5j](#). The responses of the MDB C.G. and door are compared in [Figures 5k and 5l](#) for LINCAP and IIHS side impact test conditions respectively. As can be seen in [Figure 5i](#), it is possible that some of the accelerometers in the impact zone could be damaged during the tests. However, the test data, before damage, are still very important and useful in terms of the model correlation effort. From a pressure sensor calibration point of view, only the responses for the first 15 ms are needed. The comparisons of structural responses shown in [Figure 5](#) were made for the



(a) Rocker@A-Pillar.



(b) Rocker@B-Pillar.

Figure 5. Responses of the vehicle structures and the MDBs obtained from tests and simulations.

entire side impact duration in this study to ensure the full vehicle model is as robust as possible.

LAGRANGIAN MODEL: DOOR STRUCTURE

The finite element door models created for the side door impact simulations are illustrated in [Figure 6](#). Since the door is the most important component in the predictions of the pressure responses, attention needs to be paid to the modeling of the door components. In this study, almost all internal and external components are included in the door model except for some cables and electric wires. As can be seen in [Figure 6a](#), all plastic door trim components including arm rest, map pockets, side panels, and speaker parts were modeled in detail. [Figures 6b](#) and [6c](#) show the models of door outer, door inner, door glass, window seal, door handle, and door hem. One of the most important door components in the prediction of pressure responses is the weather shield which can be seen in [Figures 6c](#) and [6d](#). More door internal components such as door beam, latch and window mechanisms, beltline reinforcements, air duct, pressure sensor, motors, glass guides, connection brackets, and so on can be found in [Figures 6e](#) and [6f](#).

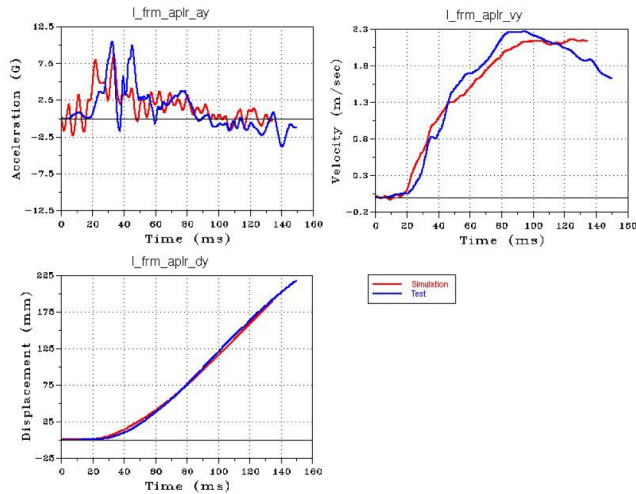
EULERIAN MODEL: AIR

In the ALE method, the air inside and outside the door is simulated with the Eulerian formulation. The dimensions of the Eulerian mesh are $1300 \times 340 \times 1430 \text{ mm}^3$ also shown in [Figures 7a](#) and [7b](#) with blue transparent color. The air inside the door can be seen in [Figures 7c](#) and [7d](#). Two Eulerian mesh sizes, $10.0 \times 1.0 \times 10.0 \text{ mm}^3$ and $10.0 \times 2.0 \times 10.0 \text{ mm}^3$, in the refined areas (as shown in [Figures 7e](#), [7f](#), [7g](#), and [7h](#)) were created in this study to cover the possible leakage areas of the door and to understand the sensitivity of the mesh size. The size of the mesh in the coarse areas is $10.0 \times 5.0 \times 10.0$

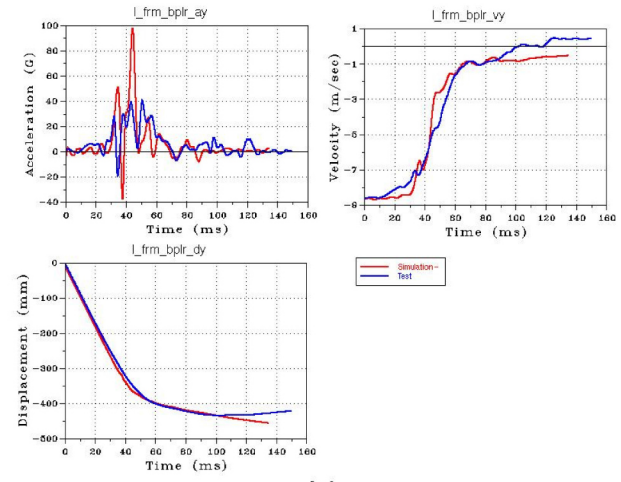
mm^3 also illustrated in [Figures 7e](#), [7f](#), [7g](#), and [7h](#). The total number of Eulerian elements is 2,044,900 for the coarse mesh system and 3,197,480 for the refined mesh system. However, numerical instability (negative volume in advection redo cycle) was encountered in the simulations with the refined mesh. Therefore, the coarse mesh system was adopted in the full vehicle simulations. Additional components, shown in [Figure 7i](#), were created for the ALE calculations and for air leakage predictions. For illustration purposes, the domain of the Eulerian mesh with respect to the Lagrangian mesh is shown in [Figure 8a](#) and [8b](#) for the regular and crew cabs respectively. To allow the Eulerian mesh to move with the door, a “moving mesh” option was adopted with a reference coordinate defined on the hinge pillar and B-pillar. The “moving mesh” option enables the minimization of the Eulerian domain. Without the moving mesh, the possible movement of the door needs to be estimated in advance and a larger Eulerian domain would be required to cover the door's movements in different impact modes. In short, the computational time and the dimension of the Eulerian domain can be minimized with the “moving mesh” option.

RESULTS AND DISCUSSIONS

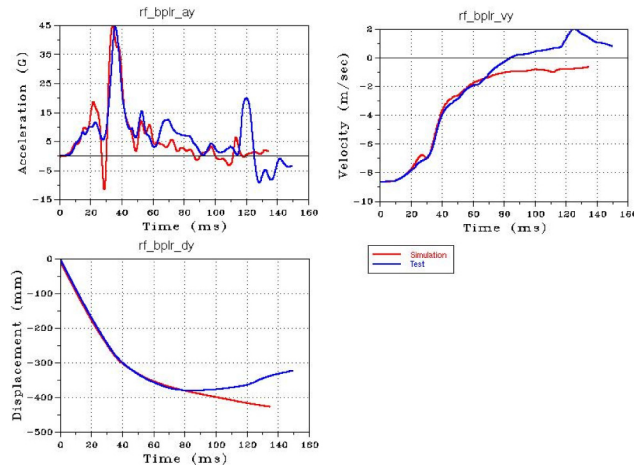
Computer simulations for all fifteen full vehicle tests were performed employing the ALE method mentioned. The ALE method employed in the simulations was the latest version with a “penalty” based, instead of a “constraint” based approach. The version employed also has the latest Eulerian-Lagrangian coupling algorithm and improved multi-material ALE capabilities. The air inside and outside the door components was defined by using an “initial volume fraction geometry” option offered in the crash code. The “initial volume fraction geometry” definition requires a closed volume in the system to identify the initial Eulerian element fraction inside or outside the Lagrangian structure parts. As a result, all holes in the system need to be covered. Other



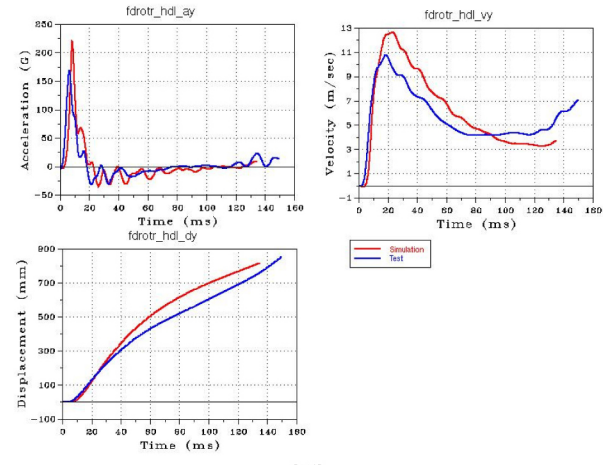
(c) Frame@A-Pillar.



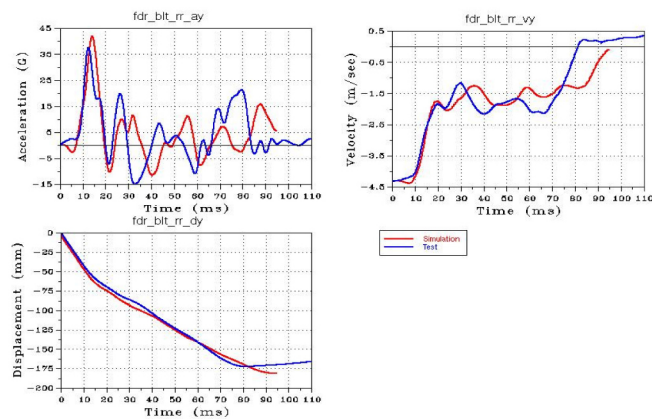
(d) Frame@B-Pillar.



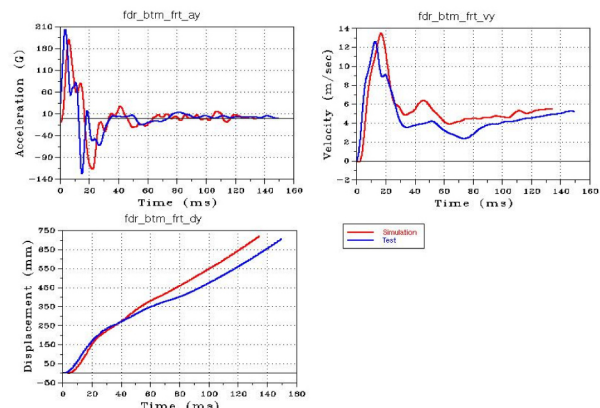
(e) Roof@B-Pillar.



(f) Door@Handle.



(g) Door@Beltline (Rear).



(h) Door bottom (Front).

Figure 5 (cont). Responses of the vehicle structures and the MDBs obtained from tests and simulations.

parameters such as NQUAD and SP (single precision) or DP (double precision) also have been studied with the optimized parameters being used in the models. In addition, a

*CONSTRAINED_LAGRANGE_IN_SOLID command card was defined for the coupling calculations between the