

# Side Crash Pressure Sensor Prediction: An ALE Approach

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## ABSTRACT

An Arbitrary Lagrangian Eulerian (ALE) approach was adopted in this study to predict the responses of side crash pressure sensors in an attempt to assist pressure sensor algorithm development by using computer simulations. Acceleration-based crash sensors have traditionally been used to deploy restraint devices (e.g., airbags, air curtains, and seat belts) in vehicle crashes. The crash pulses recorded by acceleration-based crash sensors usually exhibit high frequency and noisy responses depending on the vehicle's structural design. 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. Therefore, the sensor algorithm developments for acceleration-based sensors are mostly based on physical testing.

With the advancement in the crash sensor technology, pressure sensors that detect pressure change in door cavities have been developed recently and production vehicle applications are increasing. The pressure sensors detect pressure change when there is a change in the door volume. Due to the nature of pressure change, the data obtained from side crash pressure sensors exhibits lower frequency and less noisy responses which are quite different from those of the acceleration-based crash sensors. The technology is most promising for side crash applications due to its ability to discriminate crash severities and deploy airbags earlier. The lower frequency and less noisy responses are also more suitable for non-linear finite element codes to predict.

To help understand the responses of pressure sensors and obtain reliable test data for model developments, fourteen different benchmark tests were designed and performed in this research. The first set 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. The second set 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. Different speeds were chosen in the second set of component tests to obtain the corresponding responses. The third set 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 set of the benchmark tests; different speeds were chosen to create different crash severities. Computer simulations for all fourteen benchmark tests were conducted by employing the ALE method as one of the studies in this research. The results obtained from the benchmark tests and the computer simulations are presented and discussed in this paper.

**CITATION:** Tyan, T., McClain, B., Arthurs, K., Rupp, J. et al., "Side Crash Pressure Sensor Prediction: An ALE Approach," *SAE Int. J. Mater. Manf.* 5(2):2012, doi:10.4271/2012-01-0046.

## INTRODUCTION

Acceleration-based crash sensors have been used in the automotive industry extensively in conjunction with inflatable restraint devices such as, airbags, air curtains and seat belts. The data obtained from the crash sensors in different impact conditions is used by sensor engineers to develop deployment algorithms for restraint devices. The data recorded by the acceleration-based crash sensors usually

exhibits high frequency and noisy responses due to the crush and folding of structural components. 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. Therefore, sensor engineers primarily rely on physical testing to develop firing algorithms for acceleration-based sensors.

With the advancement of crash sensor technology, pressure sensors that detect dynamic pressure change in door

cavities have been developed recently and are being gradually implemented for side crash applications. The pressure sensors detect pressure change as soon as the door volume starts to reduce in the event of a side crash. Due to the nature of pressure change, the data recorded from side crash pressure sensors exhibits lower frequency and less noisy responses. The responses are significantly different from those of the acceleration-based crash sensors. The technology enables earlier detection of crash severity and earlier deployment decision-making for side crash applications. The lower frequency and less noisy responses are also more suitable for non-linear finite element codes to predict. The main goal of this study is to explore the possibility of using computer simulations to predict the pressure sensor responses and help sensor algorithm developments.

Based on the available CFD (Computational Fluid Dynamic) 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 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 effect can not be obtained. As a result, the method is usually used to estimate the interaction of a dummy or an occupant with fully deployed (in-position) airbags or air curtains. The UP method also has been adopted 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 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 formulation 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 tank sloshing and 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 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 ALE formulation to predict the dynamics 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 can not 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 by using the ALE formulation 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 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 deployment of side air curtains through interior trims.

The prediction of side crash pressure sensor responses involves the modeling of the door structure and the air inside

the door cavity. Physically, it is very similar to the modeling of fuel tanks and/or airbags. 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 during side impact conditions by adopting the ALE calculation. As expected, the door responses with air consideration inside door cavity were found to be quite different from those without air consideration. It was also shown that the use of the ALE formulation to model the air allowed reasonable predictions of air pressure inside the door in a variety of side impact conditions. Recently, Lin and Jerinsky [26] adopted both the UP and the ALE methods to predict the side door pressure responses with focus on full vehicle side impact conditions. They concluded that the ALE method, although requiring more computation time, is able to predict more accurate results in the early phase of the impact, whereas the UP method can predict only the average door pressure. It was also reported in the paper that both the ALE method and the UP method can be used to predict the pressure change from sensor algorithm development point of view.

## BENCHMARK TESTS

A total of fourteen benchmark tests were designed and conducted in this research to help understand the responses of pressure sensors and to obtain reliable data for model developments. The factors considered when designing the benchmark tests included different structures, opening sizes, opening locations, sensor locations, impactors, and impact speeds. The fourteen benchmark tests can be divided into three different sets. The first set of benchmark tests was designed hypothetically without any physical test being conducted. The second and third sets of the benchmark tests involved physical tests that were conducted by using a VIA dynamic sled test facility.

The first set, with only one hypothetical test, was created to check the numerical accuracy of the ALE method. In this benchmark test, a simple rectangular container was designed to simulate a piston compression condition with which the theoretical solution could be derived. For simplicity, the piston and the container were assumed to be rectangular and rigid. Two different gases with gamma (heat capacity ratio= $C_p/C_v$ ) equal to 1.01 and 1.4 (air) were assumed inside the container. No leakage between the piston and container was allowed in this case. The compression speed was assumed to be a constant so that the volume change of the rectangular container could be calculated and air pressure change relative to the piston displacement could be derived theoretically.

The second set of benchmark tests, eight component tests, involved a rectangular steel box that was slightly different from the first set. Two impactors, a rigid impactor and a deformable barrier, hit the rectangular steel box with two different impact speeds. The two different impact speeds

allowed the pressure change due to the strain rates of the air and the steel box to be distinguished. The deformable barrier was obtained by using the center portion of a standard FMVSS (Federal Motor Vehicle Safety Standard) 214 moving deformable barrier (MDB) with 400 mm width. The intention was to simulate the FMVSS214 or LINCAP (Lateral Impact New Car Assessment Program) test conditions. The rigid impactor was designed with its dimension, 400mm wide, similar to that of the deformable barrier except it was made out of steel so that no plastic deformation would occur during the tests. Boxes with and without a hole were designed in the second set of benchmark tests to understand the pressure loss due to the existence of a hole.

The third set of benchmark tests, five component tests, involved a production vehicle side door. The same rigid and deformable impactors as those used in the second set of benchmark tests were used in this set of tests. The same doors with different openings were tested to simulate different door designs. The production door with its plastic trim and side mirror removed was chosen as the baseline door. In the baseline door, the air could escape through the gap between the glass weather seal and the side mirror opening. Then the weather seal surrounding both sides of the glass along with some plastic fasteners on the door inner were removed to simulate a different door design with more openings. In this case, more air was allowed to escape due to the additional openings created on the door. Slightly different from the second set of benchmark tests, three different impact speeds were chosen in this set of tests to create different crash severities and to record the pressure change due to the strain rates of the air and the door.

## SIMULATION RESULTS

Computer simulations for all fourteen benchmark tests were performed by employing the ALE method as one of the studies in this research. Different approaches were also adopted in this research and the findings will be documented separately [27, 28]. The ALE method employed in the simulations was the latest version with a new penalty based (instead of the old constraint based) Eulerian-Lagrangian coupling algorithm and with improved multi-material ALE capabilities. Initial volume fraction geometry was used to define the air inside and outside the structure components. All holes were covered and meshed initially since the initial volume fraction geometry requires a closed volume in the system to identify the Eulerian element fraction inside or outside the Lagrangian structure parts. The coupling interaction between the Lagrangian structure (slave) entity and the Eulerian air (master) entity was defined by using a \*CONSTRAINED\_LAGRANGE\_IN\_SOLID command card. The results obtained from the ALE method are presented and discussed in the following.

LS-DYNA keyword deck by LS-PrePost

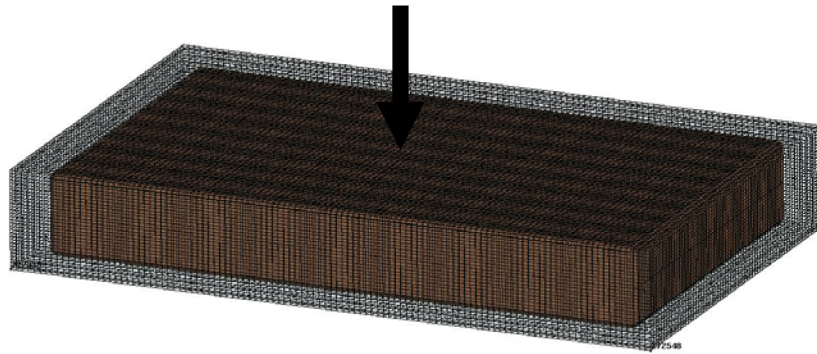
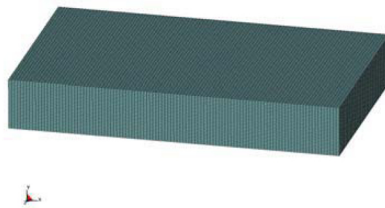


**Figure 1. Illustration of a rectangular container being compressed downward by a piston.**

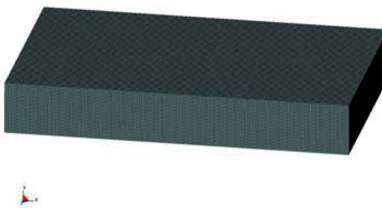
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(a) Coarse mesh.



(b) Fine mesh.



(c) Air mesh inside & outside container.

**Figure 2. Eulerian meshes representing the gas inside and outside the container.**

## A. PISTON COMPRESSION TEST

As mentioned previously, the piston compression test was designed hypothetically so that its theoretical solution could be derived and no physical test was needed. The container being compressed is shown in [Figure 1](#) in brown color, with dimensions  $1100 \times 150 \times 650 \text{ mm}^3$ . The top side of the container ( $1100 \times 650 \text{ mm}^2$ ) is being compressed downward, along the y-axis, to simulate a piston moving toward the bottom of the container. The volume of the container is reduced and the air pressure inside the container will rise once the piston starts to move downward. The piston compression test is assumed to be an isentropic process so that no heat is added to the system and no energy transformations will occur during the entire compression process. Since no physical test is involved, this case will allow the numerical error of the ALE method to be estimated.

The dimension of the Eulerian mesh is  $1200 \times 180 \times 750 \text{ mm}^3$  also shown in [Figure 1](#) with gray transparent color.

Two Eulerian mesh sizes,  $11.0 \times 6.0 \times 11.5 \text{ mm}^3$  and  $5.5 \times 3.0 \times 5.75 \text{ mm}^3$  as shown in [Figure 2a](#) and [2b](#), were chosen in this study to represent the gas inside and outside the container ([Figure 2c](#)) and to understand the sensitivity of the mesh size. The total number of Eulerian elements is 214,502 for the coarse mesh system and 1,716,000 for the refined mesh system. The size for the Lagrangian elements is  $10 \times 10 \text{ mm}^2$  for the non-deforming sides (top and bottom) and  $65 \times 10 \text{ mm}^2$  for the deforming sides. The total number of elements for the Lagrangian mesh is 15,676. For illustration purposes, only the results obtained from the coarse mesh are presented for the gas deformation mode. [Figure 3](#) shows the deformation of the gas inside the container (from the coarse Eulerian mesh) at different compression stages. Due to the accumulated error, the simulation was terminated at 80% compression.

The results of the predicted pressure responses for both mesh systems are compared to that of the theoretical solution and shown in [Figure 4](#) for gamma equal to 1.01 and 1.4.

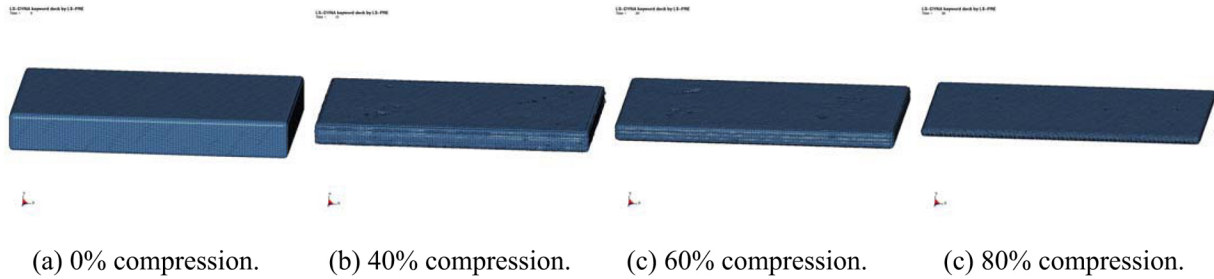


**Figure 3. The gas inside the container at different compression stages.**

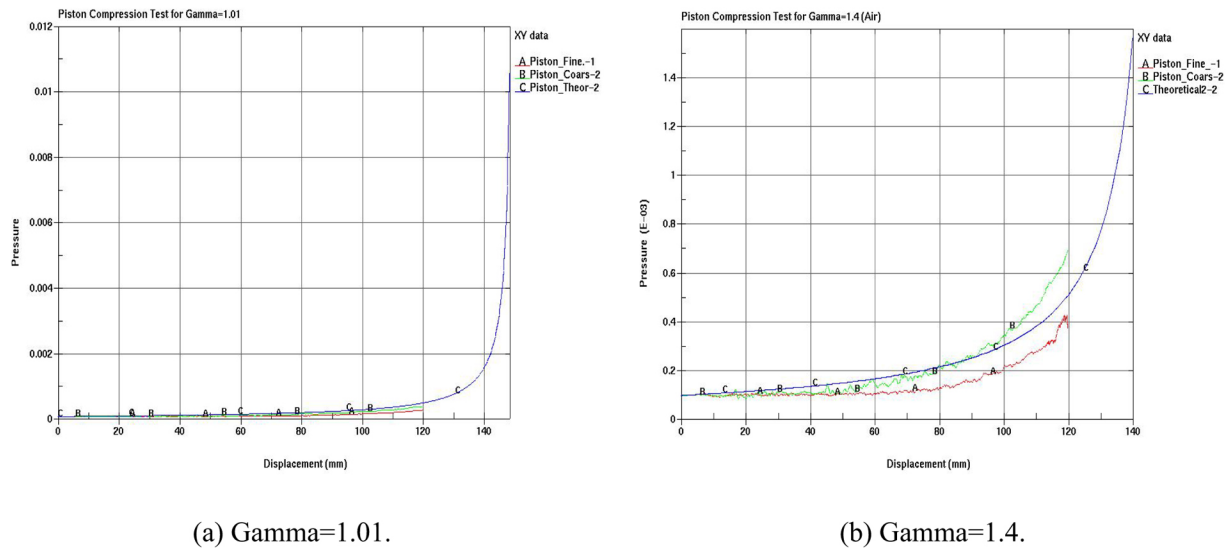


**Figure 4. Comparison of numerical and theoretical solutions.**

Indicated in the legend, the pressure response obtained from the fine mesh is plotted in red solid line, coarse mesh in green solid line, and test or theoretical solution in blue solid line. It should be noted that the same legend definition is used for every plot throughout the paper except for the box impact tests with deformable impactor.

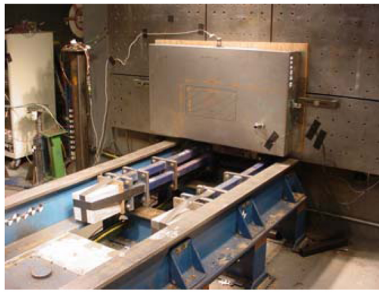
As can be seen from [Figure 4](#), the predicted pressure responses are lower than those of the theoretical solutions especially the simulations with the refined Eulerian mesh. Gas leakage was found in the simulation, which explains the lower pressure prediction. The predictions of the coarse mesh seem to be slightly better than those of the refined mesh. The coarse mesh induces less gas leakage because its element sizes are closer to those of the Lagrangian elements.

In this simulation, a boundary prescribed final geometry was used to control the piston movement. The Lagrangian elements on the four deforming sides of the container need to be balanced between the time step and its compatibility with the Eulerian elements. If larger Lagrangian elements were used, the time step would be larger but the compatibility with the Eulerian elements would be lost and the gas leakage would occur. If smaller Lagrangian elements were used to maintain the compatibility with the Eulerian elements then

the time step would be smaller. For this case with the refined Eulerian mesh (1,716,000 elements), it required 57 hours, 58 minutes, and 19 seconds of computation time with 32 MPP processors. The computation time for the coarse Eulerian mesh (214,502 elements) was 1 hour, 32 minutes, and 22 seconds with 32 MPP processors. It is expected that the gas leakage can be reduced and the prediction can be improved if more refined Lagrangian mesh was adopted. However the required computation time for the refined Lagrangian mesh would be even higher and beyond practical limits. In [Figure 4b](#), the predicted pressure of the coarse Eulerian mesh is higher than that of the theoretical solution after 90 mm of piston compression. The higher pressure is an indication that the Eulerian mesh is not fine enough. In short, this problem presents a significant challenge for the ALE calculation due to its conflicting requirements for the Lagrangian and the Eulerian meshes.

## B. BOX IMPACT TESTS

Rectangular steel boxes, with dimensions  $1100 \times 150 \times 660$  mm<sup>3</sup> as shown in [Figure 5a](#), were manufactured for the second set of benchmark tests. Mild steel available in stock was chosen to make the boxes. The VIA dynamic sled testing



(a) Steel box in the VIA Sled.

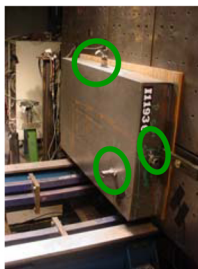


(b) Rigid impactor.



(c) Deformable impactor.

**Figure 5. The box, rigid impactor, and MDB impactor used in the VIA SLED component tests.**



(a) Pressure sensor locations.



(b) Steel box with a RHS hole.



(c) Steel box with a LHS hole.

**Figure 6. The locations of the pressure sensors, RHS and LHS holes installed around the steel box.**

facility is shown in [Figure 5a](#) with a box mounted on a wall. The seal of the box was checked prior to each test to ensure there was no leakage. The two impactors, rigid and deformable, designed for this research are shown in [Figure 5b](#) and [5c](#) respectively with which the end of the VIA sled track is also shown. Three pressure sensors were instrumented on the front, top, and side of the steel box as can be seen from [Figure 6a](#). The locations of the three pressure sensors were kept the same for all box impact tests. For boxes with holes, the locations of the right and left hand side holes can be found in [Figures 6b](#) and [6c](#). The sizes of the holes, 2"×4", were also kept the same for all the box tests conducted in the research.

The finite element models created for the box impact tests, including rigid and deformable impactors, are illustrated in [Figure 7](#). The size of the elements adopted to mesh the steel box is around 10 mm with a total of 34,978 elements. The locations of the three pressure sensors are modeled according to the test as can be seen from [Figure 7c](#). [Figure 7c](#) also shows the case of a box with a RHS hole. Two Eulerian mesh sizes, 11.0×16.8×11.5 mm<sup>3</sup> and 5×5×5 mm<sup>3</sup>, as shown in [Figures 8a](#) and [8b](#) were chosen in this study to represent the air inside and outside the box ([Figure 8c](#)) and to understand the sensitivity of the Eulerian mesh size. The total number of the air elements is 107,910 for the coarse mesh system and 1,824,000 for the fine mesh system. The same Lagrangian structure mesh was used consistently

between the simulations with the coarse or the fine Eulerian mesh.

## I. Rigid Impactor

Four tests were conducted for the box impacted with the rigid impactor. To understand the sensitivity of impact speed to the pressure response, the baseline box design without any hole was used in the first two tests, the first one with a lower impact speed and the second one with a higher impact speed. Then the boxes with a RHS hole and a LHS hole were tested subsequently to investigate the sensitivity of the pressure responses due to the addition of holes and hole location. The results of the four rigid impactor tests are presented and discussed in the following.

### 1. Low Speed without a Hole

The target speed for this low speed impact test was 5 mph while the actual impact speed reached was 4.92 mph. To prevent the impactor from damaging the VIA Sled, honeycomb blocks were used to artificially slow down the sled after 50 ms (milli-second). Therefore the comparison of pressure responses between the simulation and the test is made only for the first 50 ms, as shown in [Figure 9](#) for the three sensor locations. The comparison of the deformation mode is shown in [Figure 10](#). As can be seen from [Figure 9](#), the predicted pressure responses are reasonable for both mesh systems while the ones predicted by the refined mesh are much closer to those of the tests. The shock wave propagated