

Side Impact Pressure Sensor Predictions with Computational Gas and Fluid Dynamic Methods

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ABSTRACT

Three computational gas and fluid dynamic methods, CV/UP (Control Volume/Uniform Pressure), CPM (Corpuscular Particle Method), and ALE (Arbitrary Lagrangian and Eulerian), were investigated in this research in an attempt to predict the responses of side crash pressure sensors. Acceleration-based crash sensors have been used extensively in the automotive industry to determine the restraint system firing time in the event of a vehicle crash. The prediction of acceleration-based crash pulses by using computer simulations has been very challenging due to the high frequency and noisy responses obtained from the sensors, especially those installed in crush zones. As a result, the sensor algorithm developments for acceleration-based sensors are largely based on prototype testing. With the latest advancement in the crash sensor technology, side crash pressure sensors have emerged recently and are gradually replacing acceleration-based sensor for side crash applications. Unlike the acceleration-based crash sensors, the data recorded by the side crash pressure sensors exhibits lower frequency and less noisy responses. The lower frequency and less noisy response characteristics are more suitable for CAE (Computer Aided Engineering) predictions.

Fifteen benchmark tests, in three groups, were designed and conducted to better understand the pressure sensor responses under different impact conditions and to provide data for the evaluation of the three computational gas and fluid dynamic methods. The first group of benchmark tests included a piston compression test with two different gases being compressed in a rectangular container. The second group of benchmark tests consisted of a rigid impactor or a deformable barrier hitting a rectangular steel box with and without a hole as well as at different impact speeds. The third group of benchmark tests involved a rigid impactor or a deformable barrier hitting a vehicle side door with different openings and at different impact speeds. To ensure the robustness of CAE predictions for different test conditions, variables such as, structural design, hole size, hole location, sensor location, impactor type, and impact speed, were considered when designing the fifteen benchmark tests.

To choose appropriate approaches for side crash pressure sensor predictions, three computational gas and fluid dynamic methods available for SFI (Structure-Fluid Interaction) applications were evaluated in this research. The three methods, including two computational gas dynamic methods, the CV/UP and CPM methods, and one computational fluid dynamic method, the ALE method, were employed to simulate the fifteen benchmark tests and to understand their corresponding numerical performances. The predictions of the benchmark tests including the structure deformation mode and the pressure response are compared to those of the tests. The advantages and limitations of each method for the different variables are discussed in details based on the results obtained from the numerical simulations. In addition, computation efficiency and user-friendliness for the three methods are also compared. In addition, four full vehicle tests were selected to assure that the pressure sensor prediction capability can be used in the full vehicle test environments. The main objective of this research is to identify the most appropriate methods to predict pressure sensor responses and to enable computer simulations for the development of restraint deployment algorithms associated with the side crash pressure sensors. It is also hoped that the enhancements and developments made throughout this research would allow the three methods to be applied to a broader range of SFI problems.

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INTRODUCTION

Acceleration-based (also called G-based) crash sensors have been used extensively in the automotive industry to detect crash severity and determine the restraint system deployment time in the event of a vehicle crash. The acceleration-based crash sensors record the deceleration pulses that are created by the deformation of vehicle components. Depending on the locations of the crash sensors and the structure designs, the acceleration (or deceleration) pulses recorded by the acceleration-based crash sensors are usually noisy; especially those installed in crush zones and/or obtained from body-on-frame vehicles. The prediction of acceleration crash pulses using computer simulations has been very challenging due to the high frequency and noisy responses obtained from the sensors. As a result, the sensor algorithm developments for acceleration-based sensors are primarily based on prototype testing.

A. Pressure Sensors

With the latest advancement in the crash sensor technology, side crash pressure sensors have emerged recently and been adopted increasingly in the automotive industry. The pressure sensors detect the dynamic air pressure change in a door system with cavities. When a door is deformed, the change in the door cavity volume creates pressure change which is recorded by the pressure sensors. Unlike the acceleration-based crash sensors, the data obtained from the pressure sensors exhibit lower frequency and less noisy responses. In addition, the pressure sensors also offer the potential of earlier deployment times, more robust response, and less sensitivity to test variations. The lower frequency and reduced fluctuation characteristics have been viewed by CAE community as more appropriate to be predicted by using computer simulations. This research evaluated the advantages and limitations of the three computational gas and fluid dynamic methods, CV/UP, CPM, and ALE, with respect to the prediction of pressure sensor responses in an effort to help reduce prototype testing and improve the robustness of sensor algorithm development. A brief literature review of the developments of the three computational gas and fluid dynamic methods and their applications are summarized as follows.

B. CV/UP method

To predict the time-dependent behavior of the interior pressure of an airbag, Nefske [1] and Wang and Nefske [2] developed a CV method in the late 1980s. The CV method was also called UP method in much literature due to these assumptions that the pressure and temperature were uniform within a system at any specific time. Assuming an ideal gas law, [Equations \(1\), \(2\), and \(3\)](#) below, and an adiabatic process (no heat transfer into the control volume), [Equation \(4\)](#) below, scalar thermodynamics equations can be derived easily, (see details in Wang and Nefske [2]).

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

[Equation \(1\)](#) is the common form of ideal gas law; where P , V , n , and T denote the bag pressure [Pa], volume [m^3], number of molecules [moles], and absolute temperature [K, the Kelvin scale is a shifted Celsius scale, e.g. 0.0 K = -273.15 °C, the lowest possible temperature], respectively, while R being the gas constant [J/kg K], e.g. universal gas constant $\hat{R} = 8.3145$ J/kg K].

$$PV = \frac{m}{M}RT \quad (2)$$

[Equation \(2\)](#) is the molar form of ideal gas law; where m denotes total gas mass [kg] and M denotes molar mass [kg/mole].

$$P = \rho \frac{R}{M}T \quad (3)$$

where $\rho = m/V$ is the density of the gas [kg/ m^3].

$$PV^\Gamma = \text{constant} \quad (4)$$

where gamma $\Gamma = Cp/Cv = cp/cv$ being the heat capacity ratio of the gas ($1 < \Gamma \leq 5/3$), Cp being the heat capacity at constant pressure [J/mole K], cp being the specific heat capacity (heat capacity per unit mass) at constant pressure [J/kgK], Cv being the heat capacity at constant volume [J/mole K], and cv being the specific heat capacity at constant volume [J/kgK].

Due to the above assumption, discretization of the gas (or fluid) field is not needed. Instead, two inflow factors including mass flow rate and temperature-time relationship are needed to model the gases. The two inflow factors can be obtained through tank tests. Based on the assumptions, the gas response is not location dependent. In the application to occupant protection, the method is usually used to simulate the interaction of a normally seated dummy or an occupant with a fully deployed airbag or called “in-position” test condition. This method was also a dominating method for a long time to simplify the tire and fuel tank models that are needed in crash safety applications. In the case where the dummy or occupant contacts the airbag in an earlier stage of the deployment process such as the case of OOP (out-of-position) test conditions, more accurate methods are deemed necessary to predict the airbag transient responses reasonably.

C. ALE Method

The continuum mechanics usually adopt two classical descriptions of motion: the Lagrangian description and the Eulerian description (see e.g., Malvern [3]). The Lagrangian approach, coordinate system moving with materials, is usually adopted to describe structural problems due to the relatively smaller movement of the materials. The Lagrangian description allows an easy tracking of free surfaces and interfaces between different materials. For fluid flow problems, where the materials (fluids or gases) exhibit relatively larger 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 used to describe the structural and fluid/gas materials. In order to express the conservation laws for mass, momentum, and energy in an ALE kinematical description, a relation between material time derivative, which is inherent in conservation laws, and referential time derivative is needed. Original developments were made, among others, by Noh [4], Franck and Lazarus [5], Trulio [6], and Hirt et al. [7]. The developments were subsequently adopted in the finite element methods and early applications can be found in the work of Donea [8], Belytschko et al. [9], Belytschko and Kennedy [10], and Hughes et al. [11].

The ALE method has been regarded as one of the most advanced CFD (Computational Fluid Dynamic) methods developed for structure-fluid interaction problems today. Hughes et al. [11] adopted the ALE description in the early 1980s to solve free surface flows for incompressible viscous fluids. The Lagrangian-Eulerian description and general kinematics theory adopted by Hughes et al. [11] have served as the foundation of the ALE method in finite element computation. In the ALE calculation, discretization of both the structures and the fluid (or gas) volumes is needed. Different from the CV/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 local predictions of structure-fluid interactions. More detailed formulations of the ALE theory and computational schemes can be found in Hughes et al. [11], Benson [12], Olovsson [13], and Hirth et al. [14].

In the automotive industry, the ALE method has been used to predict the fuel sloshing in fuel tanks under high speed impact conditions. Ma and Usman [15] used the ALE formulation available in LSDYNA to design a baffle during the development of a fuel tank. Tang, Guha, Tyan, and Doong et al. [16] adopted the ALE formulation to investigate the sloshing of fuel and ballooning of deformable fuel tanks in high speed impact conditions. Recently Craig, Qu, Pan, and Tyan et al. [17] employed the ALE method to predict fuel sloshing and tank deformation. In the study, blow molding simulations were conducted to predict the thickness distribution of thermoplastic fuel tanks. In addition, fuel tank assembly process was included in the simulation to predict the pretension between the fuel tank and its straps. Reported in [17], the integration of fuel tank forming and assembly processes as well as the employment of the ALE method not only made it possible to predict the pre-tension of tank straps, but also has contributed to the accuracy of the fuel tank modeling for high speed impacts.

In the aerospace, manufacturing, and defense industries, the ALE method has also been adopted for various applications such as bird strike, bulk metal forming, air blast, gun launch, and so on. Souli and Olovsson [18, 19] 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 application of the ALE method to the bird strike problems can also be found in McCallum and Constantinou [20] and Anghileri et al. [21]. Many bulk metal forming processes, including extrusion, cutting, and punching, were simulated by employing the ALE method as illustrated by Gadala and Wang [22] and Movahhedy et al. [23]. Slavik [24] implemented a coupling method in LS-DYNA to allow empirical explosive blast loads to be applied to air domains described with the ALE formulation. Lapoujade et al. [25] worked with LSTC (Livermore Software Technology Corporation) to implement a new mapping technique for the air blast problems that were simulated by using the ALE method. Tabiei and Chowdhury [26] illustrated the use of the ALE method to predict the dynamics behavior of a generic gun launch. With an improved search algorithm specifically designed for explicit geometry information, a new S-ALE (Structured ALE method) method was developed by LSTC recently to speed up the calculation time and reduce memory usage for ALE simulations. The S-ALE method was applied to under body mine blast simulations by Hsieh, Vunnam, Bhalsod and Chen [27].

ALE method has also been adopted in the automotive industry for airbag deployment simulations, especially the OOP applications where the local response of transient stage cannot be predicted by using the CV/UP method. Olovsson [13], Marklund [28], Markland and Nilsson [29], and Fokin et al. [30] demonstrated how to employ the ALE method to model the inflators and the airbag deployments. Subsequently, Haufe and Weimar [31], and Lian [32], all have tried the ALE calculation to simulate the transient deployments of airbags with a focus on the OOP test condition.

D. CPM Method

Based on the kinetic molecular theory (KMT), Equation (5) below, the corpuscular particle method (CPM) in LS-DYNA was developed by Olovsson [33] in 2006 to simulate inflator firing and to predict airbag deployments in a more realistic manner. In this method, the gases are modeled as rigid particles obeying Newton's laws of mechanics and the ideal gas law, Equations (1), (2), and (3). Each particle represents multiple molecules, depending on the number of particles provided in the system intended to simulate.

$$P = \frac{2}{3} \cdot \frac{Wk}{V} = \frac{nM}{3V} (\mathcal{V}_{rms})^2 \quad (5)$$

$$Wk = \frac{1}{2} \frac{nM}{m} (\mathcal{V}_{rms})^2 \quad (6)$$

where Wk is the total translational kinetic energy of all molecules, and $\mathcal{V}_{rms}$ is the root mean square velocity of all molecule with mass m .

From Equations (1) and (6), Equation (7) can be obtained.

$$\mathcal{V}_{rms} = \sqrt{3RT/M} \quad (7)$$

The particles behave just like molecules that can store energy as they vibrate and spin. The total translational kinetic energy, Equation (6), of the particles is the same as that of the molecules. The theory also ensures the correct heat capacity ratio, $\Gamma = C_p/C_v = cp/cv$ in Equation (4), as the gases get expanded or compressed. The same properties of the gases are assigned to the particles directly. As a result, the ideal gas law, Equations (1), (2), and (3), the kinetic molecular theory, Equation (5), and thermodynamics are coupled, as seemed in Equation (7), seamlessly to allow simulations of transient gas dynamics problems.

Uniform porous materials, treated in the CV/UP or ALE methods, can be handled the same way in the CPM method. In addition, the vent holes can be modeled physically and the particles can be allowed to leak through. This method enables more realistic behavior of a system to be predicted both locally and globally. Due to the small size of the spherical particle, the CPM method will allow gases to leak through tiny vent holes, which provides an advantage over the CV/UP and ALE methods. More importantly, this approach does not encounter numerical difficulties, such as hourglass mode, element distortion, complex contact, and small time step, usually experienced with the continuum based approach.

The original objective for the development of the CPM method was to enable the applications associated with the inflation of an airbag and its interaction with an occupant, especially the OOP test conditions. Following the initial development of the CPM method, Feng and Coleman [34] adopted both the ALE and CPM approaches to simulate the deployment of an airbag through interior trims in 2008. A similar study was conducted by Lian et al. [35] to compare the ALE and the CPM methods in the OOP applications. In Lian's study, five benchmark problems were investigated to understand the performance difference between the ALE and the CPM methods. The method was further improved by Teng, Wang, and Bhalsod [36] to handle systems with initial air and multiple chambers. Lin, Cheng, and Wang [37] evaluated the CPM method for side impact airbag deployments. In addition to static and linear impactor tests, effects of inflator variations were also investigated in the study.

The prediction of side crash pressure sensor responses involves the modeling of a 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 literature review summarized above, the ALE method can be a good candidate for such applications. Machens and Wessels [38] made the first attempt in 2007 to investigate the pressure changes inside a door subjected to side impact conditions by adopting the ALE calculation. Lin and Jerinsky [39] adopted both the CV/UP and the ALE methods to predict the side door pressure sensor responses with a focus on full vehicle side impact conditions. It was reported that both the CV/UP and the ALE methods can be used to predict the pressure change from side impact sensor calibration point of view.

Recently, Tyan et al. [40] made the first attempt to predict the responses of pressure sensors by employing the CPM method. In the research, the CPM method was improved with additional capabilities developed and existing features enhanced to expand the applications of the CPM method to solve SFI problems with existing gases. Simultaneously, Tyan et al. [41] also adopted the ALE method to predict the responses of pressure sensors. In the research conducted [40, 41], fifteen benchmark tests were designed and performed to allow enhancements and assessments of the CPM and the ALE methods and to ensure the robustness of numerical predictions. Sensitivity of the pressure sensor responses to different variables including, gas type, structure design, hole size, hole location, sensor location, impactor type, and impact speed, were all investigated to better understand the responses of pressure sensors under different impact scenarios.

OBJECTIVES

In this study, the authors made another attempt to predict the pressure sensor responses for side crash pressure sensors by adopting the CV/UP method which was not included in the original research [40, 41, 42, and 43]. The predictions of the same benchmark tests including the structure deformation modes and pressure sensor responses are compared to those of the CPM and the ALE methods that were obtained and reported previously [40, 41]. The numerical performance of each method is compared based on the results obtained from the fifteen benchmark simulations. The prediction accuracy, computational efficiency, and user-friendliness of the three methods are compared and discussed in details in this paper. One of the main goals of this study is to understand the advantages and limitations of the three computational gas (CV/UP and CPM) and fluid dynamic (ALE) methods for such applications. Thus, the most appropriate methods can be identified and the corresponding modeling methodologies can be developed to assist pressure sensor algorithm development. Through the entire research, the authors and code developers worked jointly with an intention to further enhance and/or develop the three computational gas and fluid dynamic methods so that their applications to different SFI problems can be conducted as broadly, accurately, and effectively as possible.

BENCHMARK TESTS

To help understand the responses of pressure sensors and to obtain reliable data for model development, a total of fifteen benchmark tests were designed and conducted in the first phase of this research [40, 41]. The second phase of the research involved full vehicle simulations [42, 43] which were more complex due to the need to include seat systems, restraint systems, (seat belt, side air bag, and side air curtain,) dummies, and full vehicle models in the simulations. The fifteen benchmark tests have been reported in detail [40, 41] and are briefly repeated in this paper for understanding of the test rationale and the simulation scenarios. The fifteen benchmark tests were divided into three different groups.

The first group, with only one hypothetical test condition, was designed to check the accuracy and stability of the numerical methods. 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 modeling simplicity, the piston and the container were assumed to be rectangular and rigid. Two different gases, with gamma (heat capacity ratio: $\Gamma = C_p/C_v = cp/cv$) equal to 1.01 and 1.4 (air), were considered inside the container and simulated separately. No leakage between the piston and container was allowed in this case. For calculation simplicity, an isentropic process (a thermodynamic process that is adiabatic and in which the work transfers of the system are frictionless; there is no transfer of heat and the process is reversible) was assumed for the piston compression test. The compression speed was assumed to be 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.

With eight different test conditions, the second group of benchmark tests involved a rectangular steel box that was slightly larger than the container designed for the piston compression test in the first group of benchmark tests. Different steel boxes, with and without a hole, were included in the second group of benchmark tests to understand the pressure change due to the existence of a hole. In the test matrix, a hole was created at two different locations of the box so that the pressure sensitivity to hole location could be obtained also. In addition, three pressure sensors were instrumented on different sides of the box. Two impactors, a deformable barrier and a rigid impactor, impacted the rectangular steel box at two different speeds. The deformable barrier was fabricated by using the center portion of a FMVSS (Federal Motor Vehicle Safety Standard) 214 MDB (moving deformable barrier) aluminum honeycomb face with 400 mm in width. The rigid impactor was designed with its dimension, 400mm wide, the same as that of the deformable barrier except it is made out of thick steel so that no plastic deformation would occur in the impactor during the tests. As a result, the second group of benchmark tests would allow the sensitivity of pressure response to hole size, hole location, sensor location, impactor type, and impact speed to be investigated in detail. These tests were conducted using a VIA sled dynamic test facility due to the mass of the impactors and the high impact speeds needed for the tests.

Side doors from a production vehicle were used in the third group of benchmark tests, with five different test conditions. The side doors with different openings were tested to simulate different door designs. A 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 gaps between the glass and weather seal as well as the side mirror opening. Additionally, the weather seal surrounding both sides of the glass along with some plastic fasteners on the door inner were removed completely 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. The same rigid and

deformable impactors used in the second group of benchmark tests were used in the third group of benchmark tests. Three different impact speeds were chosen in this group of benchmark tests. The third group of benchmark tests were also conducted using the VIA sled dynamic test facility, with which the side doors could be tested with higher impact loads to approximate full vehicle test conditions.

FULL VEHICLE TESTS

The research was advanced into its final stage, full vehicle tests, after the completion of the above benchmark study. The full vehicle study conducted in this research, with different vehicle architectures (body-on-frame and unitized), body styles, test conditions (oblique pole side impact, IIHS side MDB, and FMVSS 214 MDB), and simulation methods (CV/UP, CPM, ALE) was too extensive to be included in this paper. To demonstrate the capability to predict pressure sensor responses in full vehicle test environments only unitized vehicles with ALE method were presented and discussed in this paper. A total of four full vehicle tests include two body styles with different powertrains, drivetrains, test modes, and impact speeds. The first three tests were utilized in the development of simulation methodology and calibration of air leakage while the fourth test was adopted to predict the pressure sensor response and validate the developed simulation methodology for full vehicle tests.

SIMULATION RESULTS

Computer simulations for all fifteen benchmark tests were performed by employing the CV/UP method in this study. The results obtained from the CV/UP method were compared to those of the tests as well as to those of the CPM and the ALE methods obtained previously. The modeling details of the CPM and the ALE methods have been discussed previously [40, 41] and are not repeated in this paper. For consistency, the same legend, with theoretical solution or test shown in red, CV/UP method in green, CPM method in blue, and ALE method in cyan, is used in the comparison of pressure sensor responses throughout the entire paper.

A. Piston Comprssion Test

The piston compression tests were designed hypothetically so that the theoretical solution could be derived and no physical tests would be required. The container being compressed is illustrated in [Figure 1](#), with dimensions of 1100X650X150 mm³. The top side of the container (1100X650 mm²) is compressed downward along the vertical 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 rises once the piston starts to move downward. An isentropic process is assumed so that no heat is added to the system and no energy transformations will occur during the piston compression process. Two different gases, with gamma ($\Gamma = C_p/C_v = cp/cv$, heat capacity ratio) equal to 1.01 and 1.4, were assumed inside the container. It should be noted that $\Gamma = 1.4$ represents dry air at 20

degrees Celsius while $\Gamma = 1.01$ represents a gas whose heat capacity at constant pressure is very close to its heat capacity at constant volume. Two cases were simulated with only one gas type considered inside the container in each simulation. Since no physical test is involved, this case allows the numerical accuracy and computational stability of each method to be evaluated and compared to the theoretical solution.

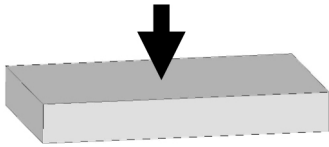


Figure 1. Illustration of a rectangular container being compressed downward by a piston.

A simple finite element model, depicted in Figure 1, was created to represent the rectangular container. The finite element model is composed of only 6 shell elements, with one shell element representing each side of the container. A “boundary prescribed motion” with uniform compression speed was defined to control the motion of the top piston. During the compression process, the top side moves downward while the bottom side is fixed which was defined by using “boundary SPC set”. The four vertical sides could become shorter and shorter as the top side moves downward. Knowing the robustness of the CV/UP method, the simulation was conducted with 99% volume compression, the same as that of the CPM method [40].

The compression of the air inside the container is shown in Figure 2 and compared with those of the CPM and the ALE methods. As expected, both the CV/UP and the CPM methods can sustain extreme compression condition with 99% volume compression without any numerical instability in this benchmark test while the ALE method exhibits leakage during the compression process. The simulation of the ALE method was terminated at 80% volume compression due to accumulated numerical error.

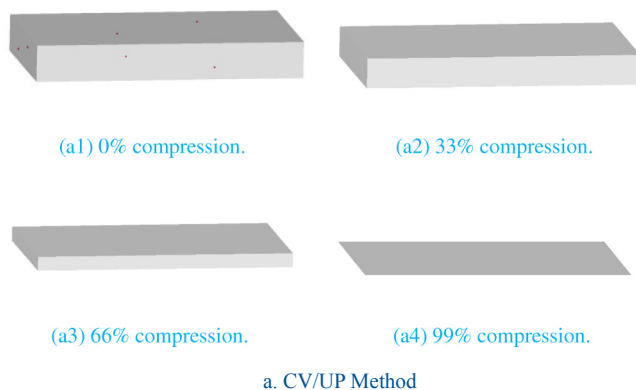


Figure 2.

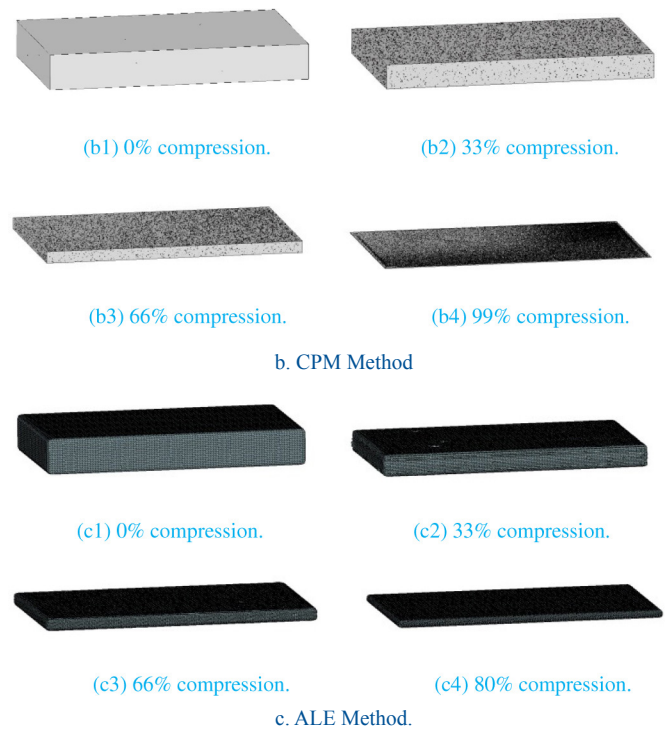
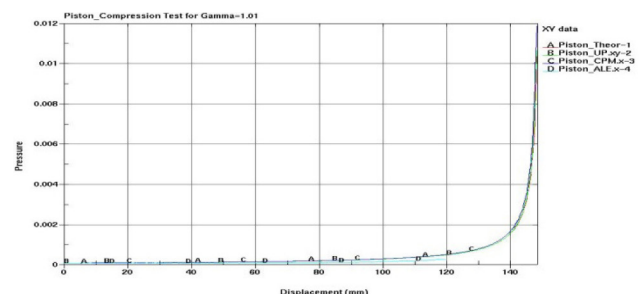


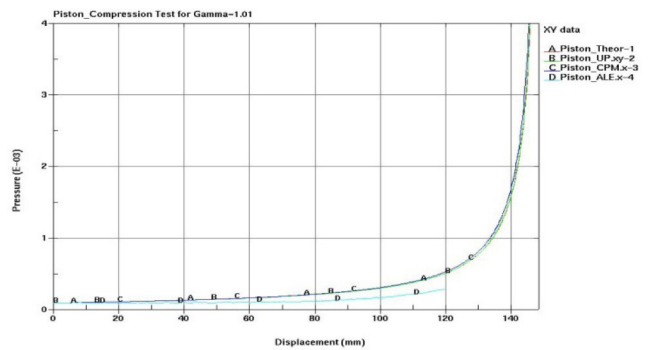
Figure 2. (cont.) Gas inside the container at different compression stages.

The prediction of the pressure response for this benchmark test is compared to those of the theoretical solutions as well as the CPM and ALE methods as shown in Figure 3. It should be noted that the unit is 10,000 bar (or kN/mm²) for all pressure sensor responses presented in this paper because the simulations used kg, mm, and ms as the base unit for mass, length, and time. The pressure sensor responses obtained from the simulations are presented without any filtering. As can be seen, the predictions obtained from the CV/UP and CPM methods almost overlap exactly with the theoretical solutions for both cases with gamma equal to 1.01 and 1.4. The predictions obtained from the ALE method for both gamma equal to 1.01 and 1.4 are lower than the corresponding theoretical solutions due to the gas leakage found in the animation of Eulerian mesh. As mentioned in [39], the conflicting requirements of the Lagrangian mesh for the box structure and the Eulerian mesh for the gas domain caused the gas leakage. The gas leakage can be reduced or eliminated but may require extensive computation time. Detailed discussion for the discrepancy of the ALE method can be found in [39] and is not repeated here.

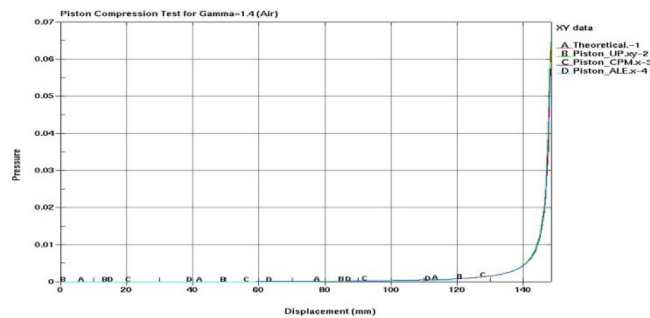


3a. Gamma=1.01: overall view.

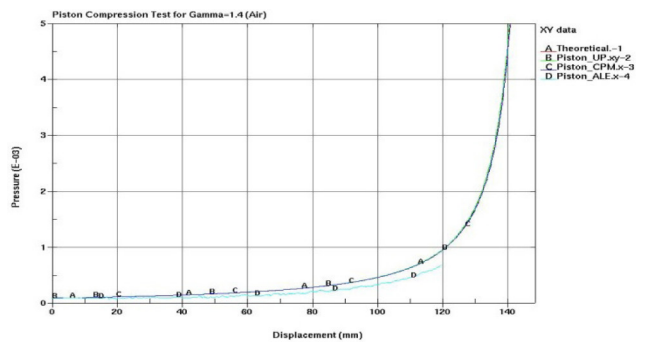
Figure 3. Comparison of numerical and theoretical solutions for 99% volume compression.



3b. Gamma=1.01: enlarged view of lower portion.



3c. Gamma=1.4: overall view.



3d. Gamma=1.4: enlarged view of lower portion.

Figure 3. (cont.) Comparison of numerical and theoretical solutions for 99% volume compression.

The computational performance for the piston compression test obtained from the three computational gas and fluid dynamic methods are compared in Table 1. The CV/UP method not only provides very accurate results, but also consumes the least amount of computation time. The CPM method also provides very accurate results but requires more computation time (1210 times) than that of the CV/UP method. The ALE method is not able to predict accurate results without more effort and requires the highest amount of computation time (491104 times the CV/UP method or 406 times the CPM method) in this benchmark test.

Regarding the user-friendliness, the CV/UP method is also the best due to the fact that no discretization is needed for the gas inside the container. The CPM method requires an appropriate number of particles to be defined for the gas but the optimal particle number can be obtained through a simple sensitivity study. The ALE method requires the gas to be meshed and the coupling of the Lagrangian and

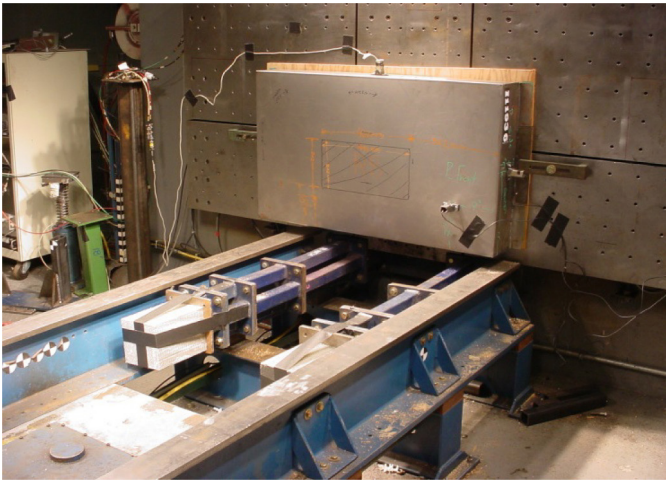
the Eulerian calculations with associated features to be defined in the input deck. The ALE method is the least user-friendly when comparing to the CV/UP and the CPM methods.

Table 1. Comparison of computation performance for the piston compression test.

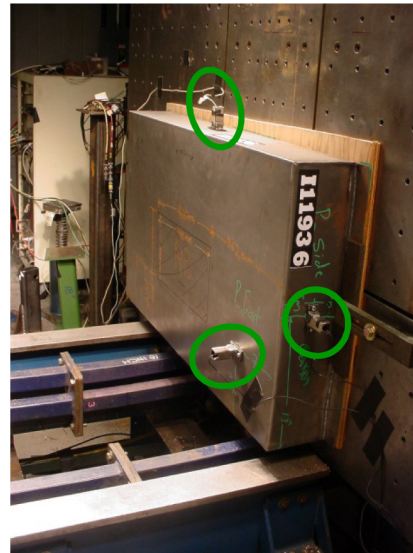
Method	CV/UP	CPM	ALE
Simulation Time	99% Compression	99% Compression	80% Compression
Air Element #	n/a	200,000 Particles	1.716 M Eulerian Elements
Computation Cycle	12000	12000	89010
CPU # (MPP)	4	4	32
Prediction Accuracy	Accurate	Accurate	No So Accurate
Elapsed Time (CPU Seconds) [Ratio]	2 s (1.3140E+01) [1/UP]	53 m 36 s (1.5896E+04) [1210/UP]	2 h 38 m 46 s (6.4531E+06) [491104/UP] [406/CPM]
User-Friendliness	Easiest	2nd Easiest	3rd Easiest

B. Box Impact Tests

As displayed in Figure 4a, rectangular steel boxes with dimensions 1100X150X660 mm³ were manufactured for the second group of benchmark tests. Mild steel available in the laboratory was chosen to make the boxes. The VIA sled dynamic test facility is shown in Figure 4. The two impactors, one rigid and one deformable, designed for this research are shown at the end of the sled track in Figures 4b and 4c, respectively. Three pressure sensors were instrumented on the front, top, and side of the steel box, as can be seen in Figure 5a (highlighted in green circles). The locations of the three pressure sensors were kept the same for all the box impact tests. The seal of the box was checked prior to each test to ensure there was no leakage. For boxes with a hole, the locations of the right or left hand side hole can be found in Figures 5b and 5c (highlighted in a green circle), respectively. The size of the hole, 2" X 4" [50mm X 100mm], was kept the same for all the box impact benchmark tests with a hole.



4a. Steel box in the VIA Sled.



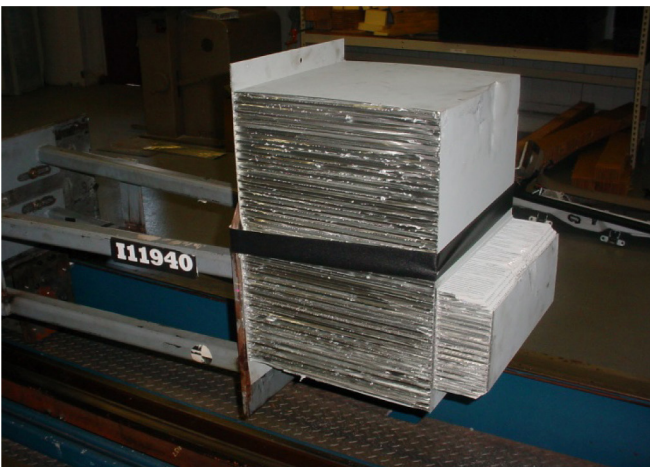
5a. Pressure sensor locations.



4b. Rigid impactor.



5b. Steel box with a RHS hole.



4c. Deformable impactor.



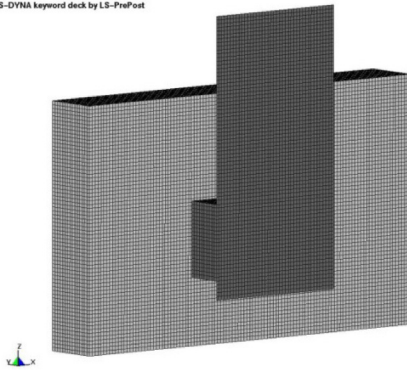
5c. Steel box with a LHS hole.

Figure 4. Box, rigid impactor, and MDB impactor used in the VIA sled dynamic impact tests.

Figure 5. Locations of the pressure sensors and holes on the steel box.

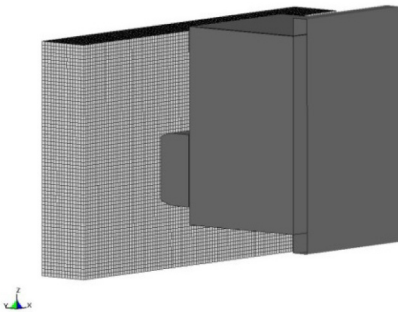
To simulate the box impact benchmark tests, finite element models created are shown in Figure 6 with the two different impactors, rigid (Figure 6a) and deformable (Figure 6b). The size of the elements adopted to mesh the steel box was around 10 mm with a total of 34,978 shell elements. The locations of the three pressure sensors were modeled according to the test, as can be seen from Figure 6c (black squares on the front, side, and top sides of the box). Figure 6c also illustrates the case of a box with a RHS hole (rectangular hole) and a deformable impactor.

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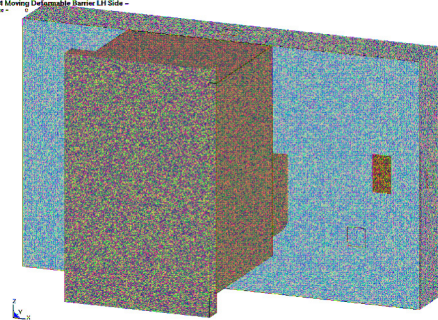
6a. Steel box with a rigid impactor.

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6b. Steel box with a deformable impactor.

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6c. Steel box with a RHS hole.

Figure 6. Finite Element models created for the steel box impact simulations.

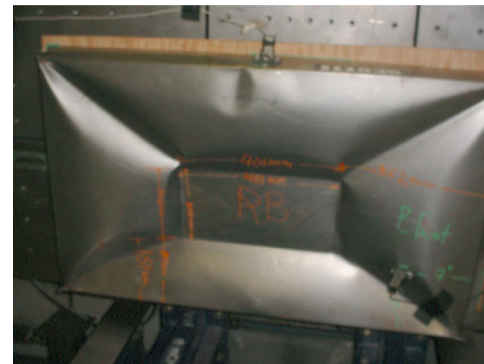
I. Rigid Impactor

Four benchmark tests were conducted for the box impacted with a rigid impactor. To better understand the sensitivity of the pressure response to impact speed, the baseline boxes without any hole were used in the first two tests, the first one with a lower impact speed and

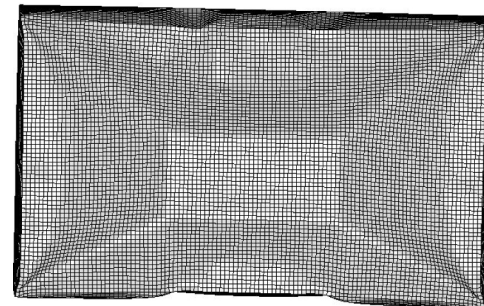
the second one with a higher impact speed. The boxes with RHS and LHS holes were subsequently tested to investigate the sensitivity of the pressure sensor responses to the hole location. From the studies conducted previously [39, 40], the pressure is not sensitive to the sensor location for the box impact tests. Therefore, the pressure response will be compared only at the top sensor location in this paper. The results of the four rigid impactor tests are presented in the following sections.

1. Low Speed without a Hole

The target speed was 5 mph [2.24 mm/ms] while the actual impact speed reached for the low speed test was 4.92 mph [2.2 mm/ms]. To prevent the impactor from damaging the VIA sled dynamic test facility, honeycomb blocks were used to artificially slow down the impactor after 50 ms. Therefore, the comparison between the simulation and the test is made only for the first 50 ms. The comparison of the box deformation mode is shown in Figure 7. It should be noted that the test picture was taken after the test; the rebound of the impactor has been completed, while the predicted deformation modes were obtained at 50 ms simulation time. As can be seen from Figures 7, the crease lines created on the box were predicted reasonably well by all the three methods. Some indentations created on the front top and front bottom were also captured in the three simulations.

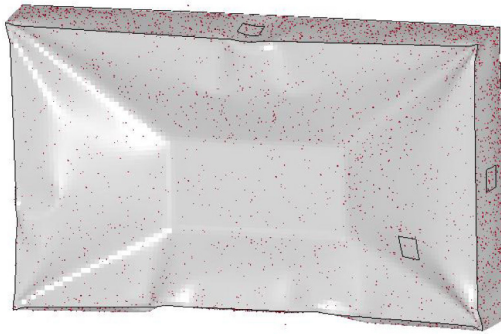


7a. Post-test box.



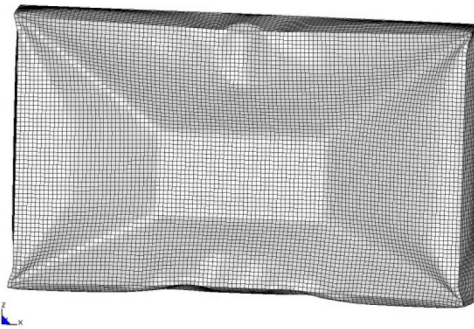
7b. CV/UP method @ 50ms.

Figure 7. Comparison of deformation modes for the low speed impact with a rigid impactor.



7c. CPM method @ 50 ms.

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7d. ALE method @ 50 ms.

Figure 7. (cont.) Comparison of deformation modes for the low speed impact with a rigid impactor.

The pressure sensor responses obtained from the three methods are compared to that of the test and shown in Figure 8. A shock wave propagated from the front side of the box and reached back sides of the box at around 10 ms. Due to the compliance of the system, the box was allowed to expand slightly when the shock wave reached the back sides of the box. The expansion of the box on the back side caused the pressure increase to slow down slightly, as can be seen from Figure 8 at around 10 ms to 17 ms. The prediction of the pressure slope change at around 10 ms to 17 ms is not trivial. The three methods are able to accurately capture the entire pressure response, including the pressure slope change between 10 ms to 17 ms. It can be seen that the pressure sensor responses predicted by the three methods are very consistent in this benchmark test.

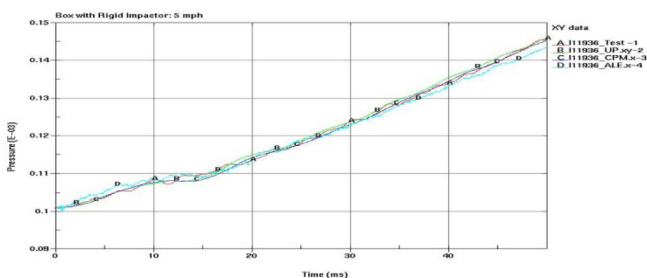
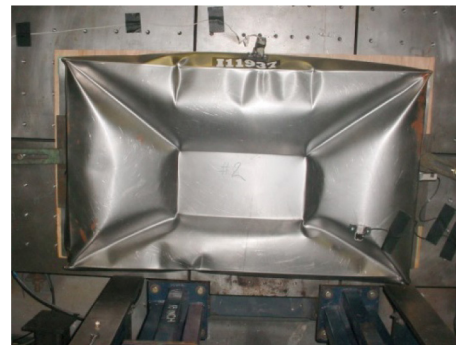


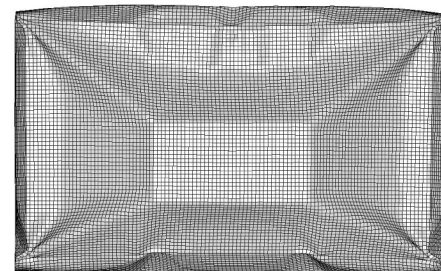
Figure 8. Comparison of pressure sensor responses for the low speed impact with a rigid impactor.

2. High Speed without a Hole

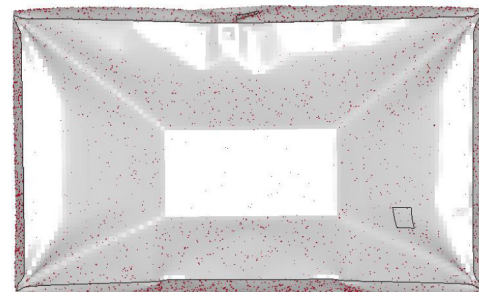
The actual speed for this test was 11.87 mph [5.31 mm/ms] while the target speed was 12 mph [5.36 mm/ms]. Due to the higher impact speed than the previous test, the rigid impactor was decelerated by the honeycomb blocks after 30 ms. Therefore, the comparison between the prediction and the test is made only for the first 30 ms. The comparison of the box deformation modes is shown in Figure 9. As expected, the box deformed more severely in this high speed impact condition compared to that of the low speed impact condition, displayed in Figure 7. In Figure 9, it should be noted again that the post-test picture was taken after the test when the rebound of the impactor has been completed while the simulation deformation modes are shown at 30 ms simulation time. Similar to the low speed impact case, it can be seen that the crease lines and indentations created on the box were predicted reasonably well by the three methods.



9a. Post test box.



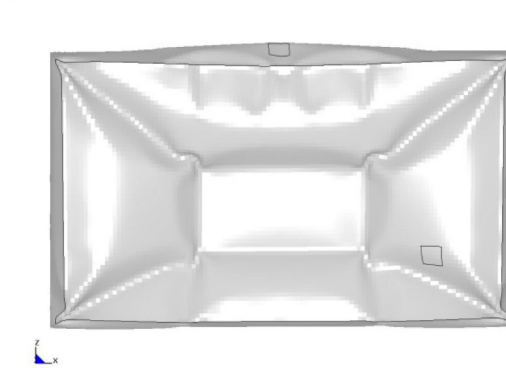
9b. CV/UP method @ 30ms.



9c. CPM method @ 30 ms.

Figure 9. Comparison of deformation modes for the high speed impact with a rigid impactor.

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9d. ALE method @ 30 ms.

Figure 9. (cont.) Comparison of deformation modes for the high speed impact with a rigid impactor.

The predicted pressure sensor responses obtained from the three methods are compared to that of the test, as graphed in Figure 10. The three methods are able to predict the pressure response accurately for the entire simulation duration, including the pressure slope change between 8 ms and 15 ms. Again, the variation among the four curves is very small for this benchmark test.

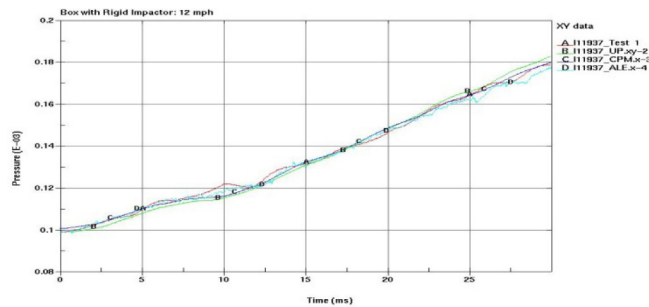
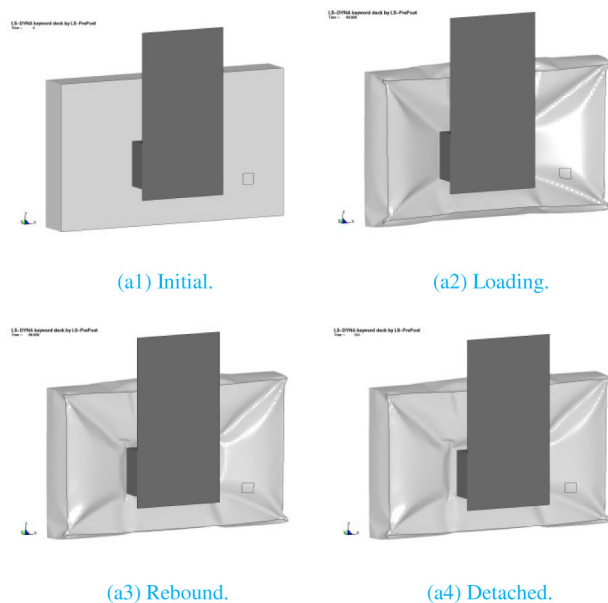
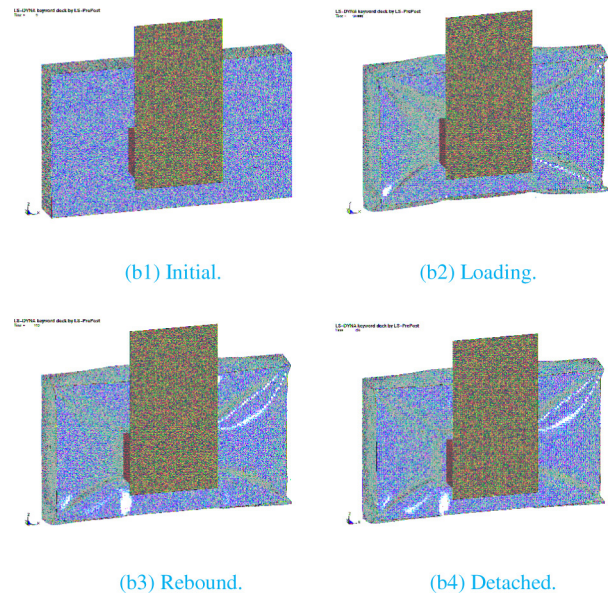


Figure 10. The comparison of pressure sensor responses for the high speed impact with a rigid impactor.

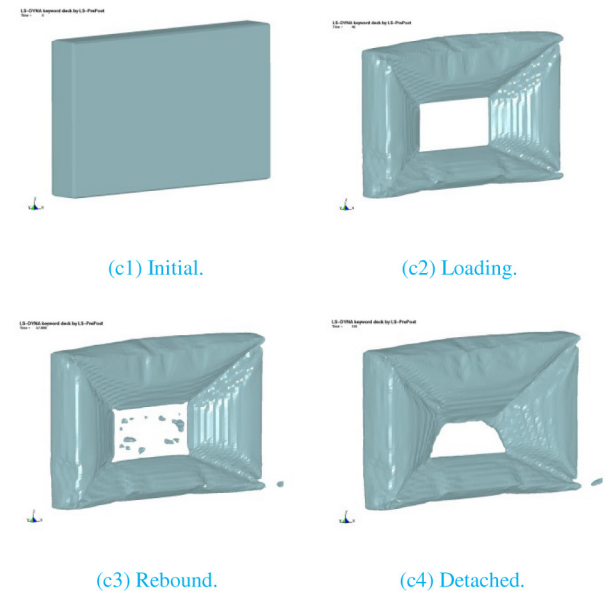


11a. CV/UP method.

Figure 11.



11b. CPM method.



11c. ALE method.

Figure 11. (cont.) Deformation modes for the case with rebound consideration.

The entire impact event of this case was simulated in this study so that the pressure sensor responses during the rebound stage could be investigated in details. To achieve such goal, the deceleration pulse obtained from an accelerometer installed in the sled was adopted and defined as the “boundary prescribed motion condition” in the three simulations. Figure 11 (11a to 11c) compares the progression of the box deformation for the three methods. As can be seen, the deformation modes obtained from the three methods are quite similar.

The comparison of the pressure sensor responses at the top sensor location with respect to time is shown in Figure 12. The predicted pressure sensor responses obtained from the three methods, including the loading and rebound stages; correlate very well with that of the test. However, the pressure sensor response obtained from the ALE method starts to fluctuate severely after around 0.05 ms.

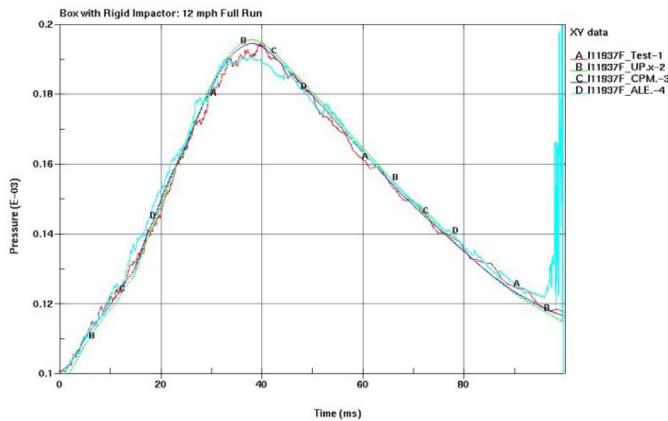


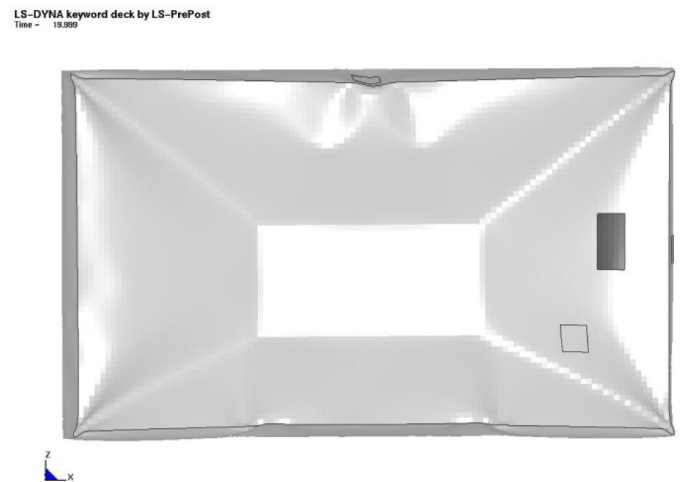
Figure 12. The pressure sensor responses for the box impact case with rebound consideration.

3. High Speed with a Right Hand Side Hole

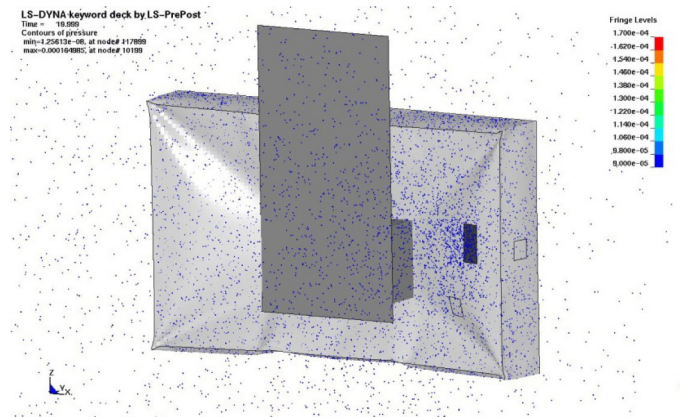
The actual impact speed for this test was 11.81 mph [5.28 mm/ms] while the target speed was 12 mph [5.36 mm/ms]. In this test condition, a hole was created on the right hand side of the box, close to the locations of the front and side pressure sensors. Again the comparison between the simulation and the test is made only for the first 20 ms before the rigid impactor is decelerated by the honeycomb blocks. Figure 13 compares the box deformation modes obtained from the test, Figure 13a, and the three simulations as shown in Figures 13b, 13d, and 13f. The air leakages through the RHS hole predicted by the CPM and ALE methods are presented in Figures 13c and 13e respectively. Similar to those of the above two cases, the predicted crease lines of the box seem to be reasonable. The box deformation patterns predicted at 20 ms from the three methods are found to be quite similar although some small differences can be identified on the indentations located on the center top of the box.



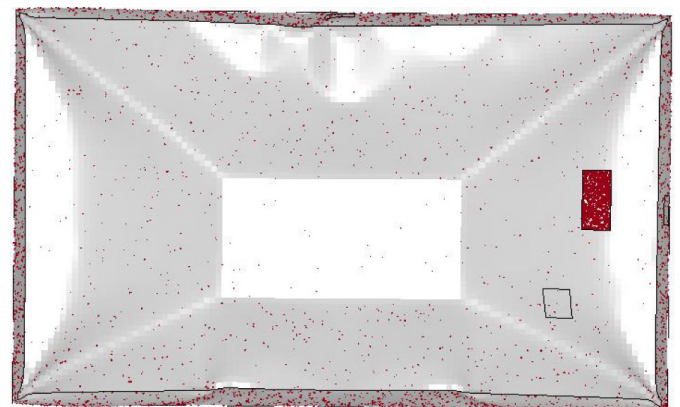
13a. Post-test box.



13b. Box deformation - CV/UP method @ 20ms.



13c. Air leakage - CPM method @ 20 ms.



13d. Door deformation - CPM method @ 20 ms.

Figure 13. (cont.) Comparison of deformation modes for the RHS hole with a rigid impactor.

Figure 13.