# Comparison of Simulations for Fluid-Structure Interaction of Water Filled Plastic Bottles during Drop Test

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**Abstract**

The simulation of drop test for water filled plastic bottle is an efficient tool for design and development of plastic bottles. In this paper, numerical models of the water filled plastic bottle during the impact with the ground were developed and validated using experimental data. Specific drop tests were carried out using simulation of plastic bottles and reproduced in detail using the MSC.Dytran program. In particular, three different numerical methods were adapted to models the water inside the plastic bottle using Lagrangian, General coupling and Arbitrary Lagrangian Eulerian (ALE) model. Compared with the experimental results, The Lagrangian and ALE models underestimated the influence of fluid-structure interaction of plastic bottles while the General coupling model could be considered as a practical method for engineering applications. Despite the large CPU time, it obtained the most accurate analysis for the drop test of fluid-filled plastic bottle.

**Keywords:** Fluid-structure interaction, Lagrangian, General coupling, Arbitrary Lagrangian Eulerian

## 1. Introduction

Injection blow mold plastic bottles have found in varieties of application for the storage of consumer products such as beverages and water. Poly ethylene terephalate (PET) is frequently the choice for such containers. The containers including bottles are subjected to a drop impact test, which requires them to be filled with water and dropped onto a hard steel plate or concrete floor to determine the maximum height from which they can be dropped without rupture. The drop test procedure is defined in testing standard [1].

Finite element method (FEM) is the aim for the efficient modeling of the drop impact test for the bottles, which is appropriate for the design and development of plastic bottles [2,3,4]. Direct FEM modeling of the complete water-filled system can be used to compute deformation and stresses in a bottle throughout the impact test. In this paper, the interaction between the structure and the fluid inside a bottle was investigated with regard to the impact with the ground by means of the explicit finite element code, MSC.Dytran.

In order to accurately simulate the impact of the bottle with the ground, the great care was dedicated to both the model of fluid inside the bottle and the interaction between the fluid and the structure of the bottle. In particular, after having realized an accurate finite element model of the bottle structure, difference numerical models were developed and validated for the fluid inside the bottle. The results obtained were evaluated comparing with the experimental data collected during the test.

## 2. Experiment

Experimental data from drop-test were obtained by conducted bottles of cylindrical form and capacities 500 ml. The bottles filled with water (500 ml) had the weight 510 grams. The release heights above the force plate were 0.5, 1.0 and 1.5 m respectively. The force plate onto which the bottles fell was a specially constructed from AMTI model OR6-7 with outputs coupled to record the total impact force. Figure 1 was shown bottle and force plate. The signals from the force plate were taken to amplifier, A/D converter and hard disc in PC, in order to record the force pulse signals. Fifteen drops at each case were conducted to ensure the repeatability of testing results. The forced traces of vertical impact angle are choose not exceed ±3 degree from vertical line. Pictures with extract from video recorder files are shown in figure 2 which is the example of the water-filled bottles released

(a) (b)

Figure 1. (a) Example of the bottle (b) The top view of the AMTI force plate model OR6-7

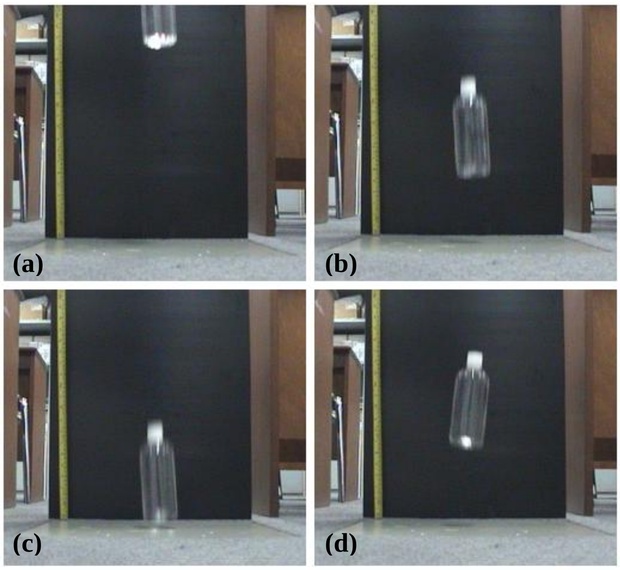



Figure 2. The experimental of water-filled drop test from 1.0 m-height.

from the height 1.0 m. The sequences of falling bottle are shown in sequent from (a) to (d). In these experiments, the force traces obtained from bottles dropped from many cases; the drop height 0.5, 1.0 and 1.5 m of the water filled bottles. All of these results included the average of results were shown in figure 3-5 respectively. The pulse traces may be characterized by their magnitude (impact-force) and duration (pulse time). Their characteristics described in table 1.

Table 1. The characteristics of pulse traces from experimental data.

| Drop height (m) | Impact-Force (N) | | | Pulse time (msec) |
|---|---|---|---|---|
| | maximum | minimum | average | |
| 0.5 | 1383.0 | 961.9 | 1188.6 | 5.5 |
| 1.0 | 1705.7 | 1387.0 | 1563.8 | 5.5 |
| 1.5 | 2234.6 | 1707.8 | 1967.2 | 5.5 |

## 3. Numerical Analysis

In order to reproduce the impact with the ground (force plate), different approaches were adopted to model the fluid inside the bottle, using Lagrangian model, General coupling model and ALE model.

The results obtained from the numerical simulations were eventually evaluated and compared with the experimental data collected during drop tests.

### 3.1 The finite element model of the bottle

The model consist of two parts, the bottle model and the force plate model, were constructed by shell elements.

The bottle was constructed from 530 quadratic shell elements. The force plate was constructed from 121 quadratic shell elements and placed under the bottle model -0.01 m. at y-direction (figure 6). In order to save computation time, the initial velocity has been assumed $v_i = \sqrt{2g(h-y)}$ where drop height is $h$ and the gap between bottle base and force plate is $y$.

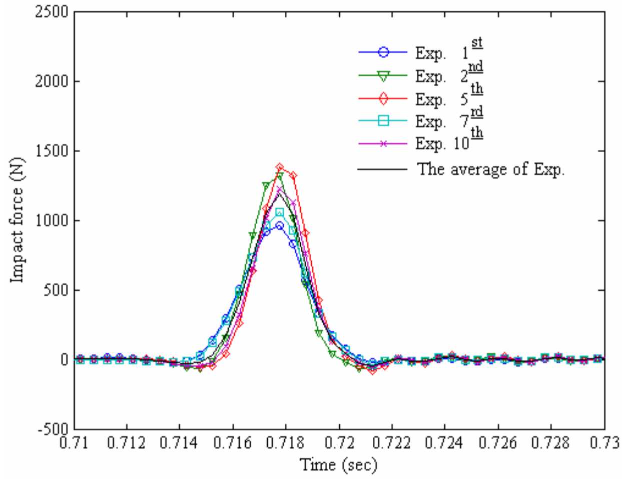



Figure 3. Force traces of the drop test water-filled bottle from 0.5 m-height.

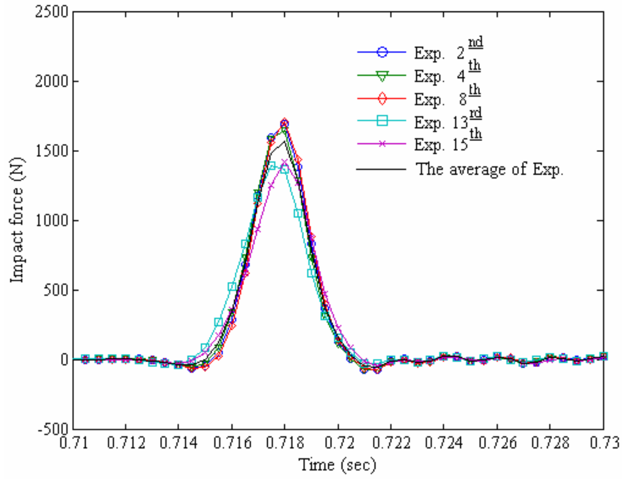



Figure 4. Force traces of the drop test water-filled bottle from 1.0 m-height.

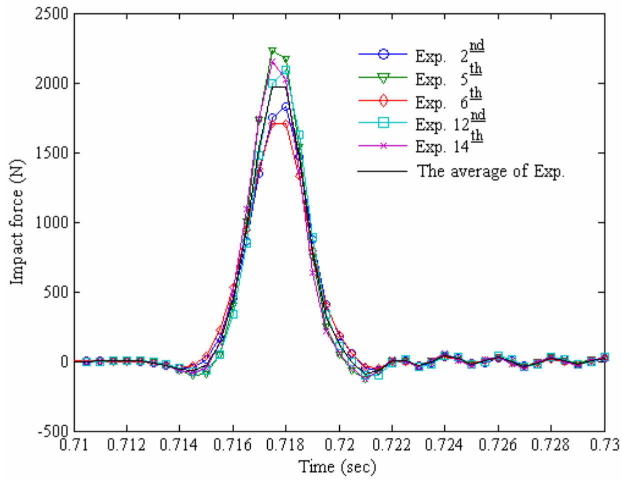



Figure 5. Force traces of the drop test water-filled bottle from 1.5 m-height.

The force plate, initially defined as a flat rigid plate, was subsequently modeled as a fixed plate made up of "rigid" material shell elements [5]. The thickness of shell elements was approximately the same layer of force place on which the bottle impacted.

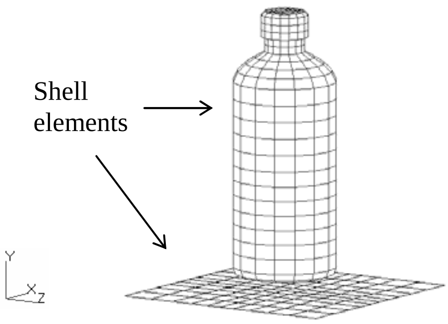



Figure 6. The bottle and force plate model

### 3.2 Model of the water inside the bottle

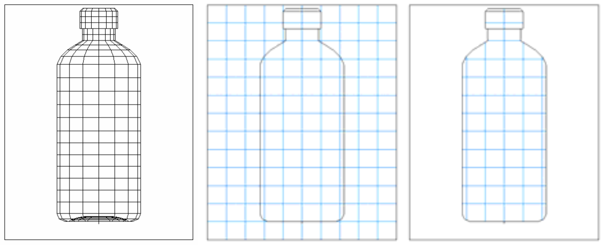
With regard to the fluid-structure interaction, the use of explicit codes based on FEM is not conventional approach. Indeed, these codes, specially developed for crush/impact problems [6], represent a useful numerical tool to develop a crashworthy structure. The effectiveness of the different cited methods was evaluated with regard to the water contained inside a bottle during the impact with the force plate. In particular, three models for the water simulation were the Lagrangian model, the General coupling model and the ALE model. The obtained results were eventually compared with experimental data.

#### 3.2.1 Lagrangian model

The Lagrangian approach is customary in the Continuum Mechanic [7] and it is powerful tool not only for the analysis of crash/impact events but also for the analysis of the fluid flow [8]. Following a Lagrangian approach to the description of the continuum mechanic, the mesh follows the material. The interaction between water and structure was modeled using the contact algorithm where the water was defined as slave part. The FE model of the water used in the simulation consisted of 1,620 eight-node solid elements. The approach of the Lagrangian model was shown in figure 7. Solid elements of water (figure7a) were put inside the shell element of bottle, and then the Lagrangian model of water-filled bottle was shown in figure7c.

#### 3.2.2 General coupling model

The General coupling algorithm is using a surface of a bottle as boundary condition to flow of the material in Eulerian mesh. During one time step within the explicit method, this boundary is calculated after the new positions of the grid points are known. It can be seen as a stationary or moving wall [9]. The water model used in the present work was constructed from 1,694 eight-node solid elements. The basic of General coupling algorithm is shown in figure 8 for the 2D case at initial step. Figure 8a shows the empty bottle or the boundary surface. Figure 8b shows the empty bottle into the space of water element (Eulerian). The General coupling model of water-filled bottle is shown in figure 8c. The boundary surface (shell element) was used to create the covered volume to generate a new control volume, which is used in the Eulerian solver. Using this advantage the General coupling surface can undergo arbitrary motions and can be of any shape as long as it has a closed volume.



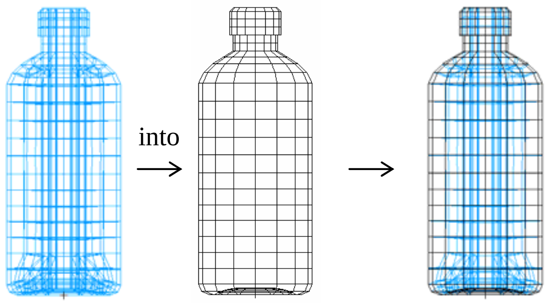
(a) (b) (c)

Figure 8. Change control volume due to the General coupling model.

#### 3.2.3 ALE model

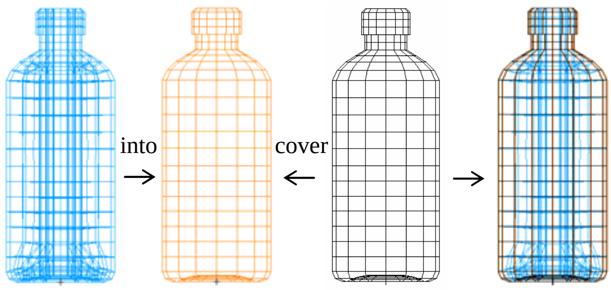
In the ALE formulation, the Eulerian mesh and the Lagrangian mesh are coupling through an ALE interface surface. The Lagrangian and Eulerian grid points in the interface surface coincide in physical space but are separated in logical space. The ALE interface moves as the Lagrangian structure deforms. Thus, the Eulerian meshes boundary moves. The fluid material flows through the Eulerian mesh as in general coupling; however, the mesh can also be made to follow the structure by defining the Eulerian grid points as ALE grid points [10].

The ALE model of the water used in the simulation consisted of 1,620 eight-node solid elements and was the same as water of the Lagrangian model. The approach of ALE was shown in figure 9. Solid elements (Eulerian mesh) in figure 9a and shell elements (Lagrangian mesh) in figure 9c were coupling through an ALE interface surface (figure 9b). The ALE model of water-filled bottled is shown in figure 9d.




(a) (b) (c)

Figure 7. The Lagrangian model of water-filled bottle




(a) (b) (c) (d)

Figure 9. The ALE model of water-filled bottle

This way the ALE interface surface stayed intact and structure as well as fluid solutions could be computed accuracy near this surface.

## 4. Results

The results obtained after the simulations performed using different models for the water inside the bottle were compared qualitatively and quantitatively among themselves and with the average data collected during fifteen drop test per drop height.

### 4.1 Maximum impact force and pulse time

The average force traces of the drop-test results from the experiment compared with FEA (three different water-filled models) for 0.5-, 1.0- and 1.5-m height were shown in figure 10-12 respectively. All FEA results correlated with the experiment except the drop-test results of the Lagrangian water-filled bottle model which the pulse time increased following by the drop height.

Impact-force and pulse time characteristics of all results were compared in table 2 and 3 respectively.

Table 2. The impact-force of FEA results compared with experiment

| Drop height (m) | Impact-Force (N) | | | |
|---|---|---|---|---|
| | Exp. (average) | Lagrangian | General Coupling | ALE |
| 0.5 | 1188.6 | 885.8 | 1047.7 | 994.3 |
| 1.0 | 1563.8 | 1087.5 | 1534.6 | 1433.1 |
| 1.5 | 1967.2 | 1281.6 | 1930.2 | 1788.5 |

Table 3. The pulse time of FEA results compared with experiment

| Drop height (m) | Pulse time (msec) | | | |
|---|---|---|---|---|
| | Exp. (average) | Lagrangian | General Coupling | ALE |
| 0.5 | 5.5 | 7 | 6 | 6 |
| 1.0 | 5.5 | 7 | 5.5 | 5.5 |
| 1.5 | 5.5 | 7 | 5.5 | 5.5 |

Figure 13 was shown the accuracy of General coupling model for investigation of maximum impact force. The average of the error between the experimental data and each the drop-test model were 30.26 %, 5.20 % and 11.26 % for Lagrangian, General coupling and ALE model respectively.

### 4.2 Deformation of bottle model

At 1.0-m drop height, the deformations of the bottles when impacted with the force plate at maximum displacement were shown in figure 14 - 16 for the drop-test simulation of the bottle with the Lagrangian, General coupling and ALE water-filled models respectively. The simulation results were shown the stress in the bottle with color spectrums. The maximum stress was red and the minimum stress was white. The result of General coupling and ALE model compared well with experiment in figure 2c and the most accurate when compared with experiment.

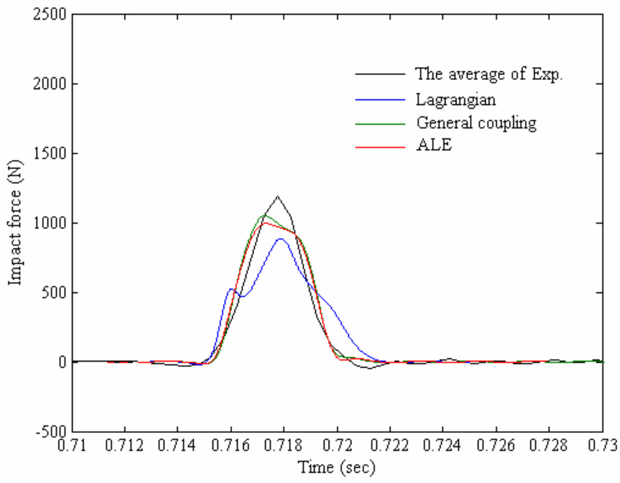



Figure 10. The average force traces of the drop test water-filled bottle from 0.5-m height compared with three different FEA.

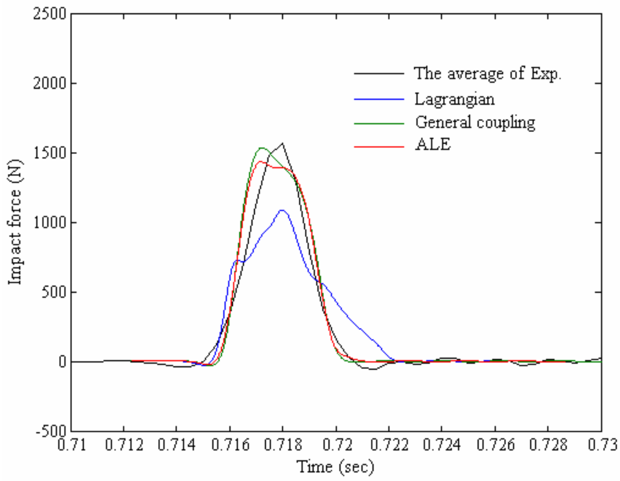



Figure 11. The average force traces of the drop test water-filled bottle from 1.0-m height compared with three different FEA.

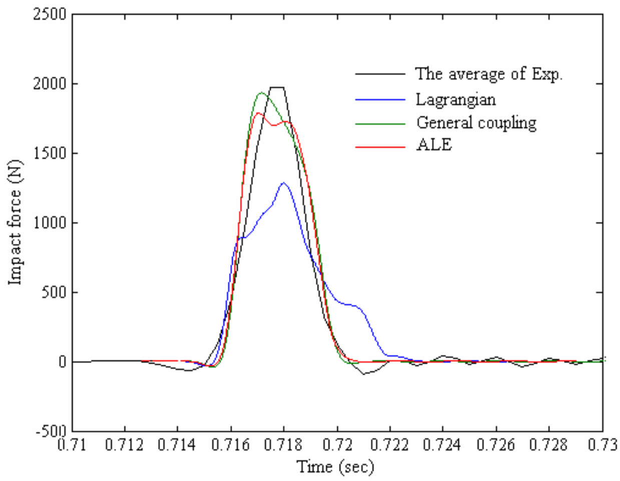



Figure 12. The average force traces of the drop test water-filled bottle from 1.5-m height compared with three different FEA.

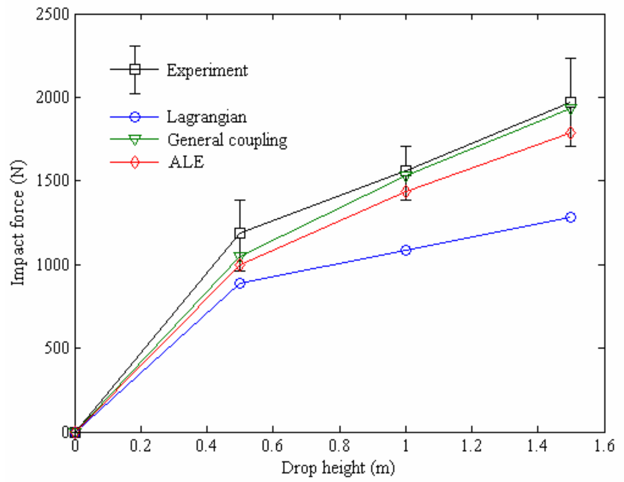


Figure 13. The impact force of drop test water-filled bottle from 0.5- to 1.5-m height compare with three different FEA

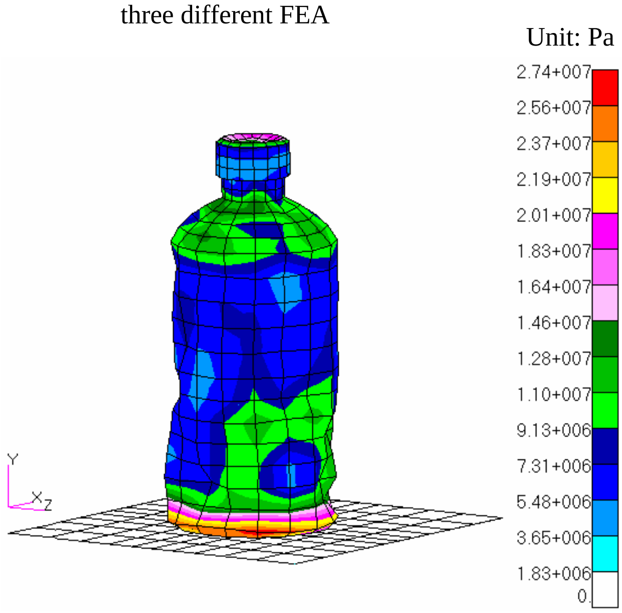


Figure 14. The drop-test of the Lagrangian model at maximum displacement.

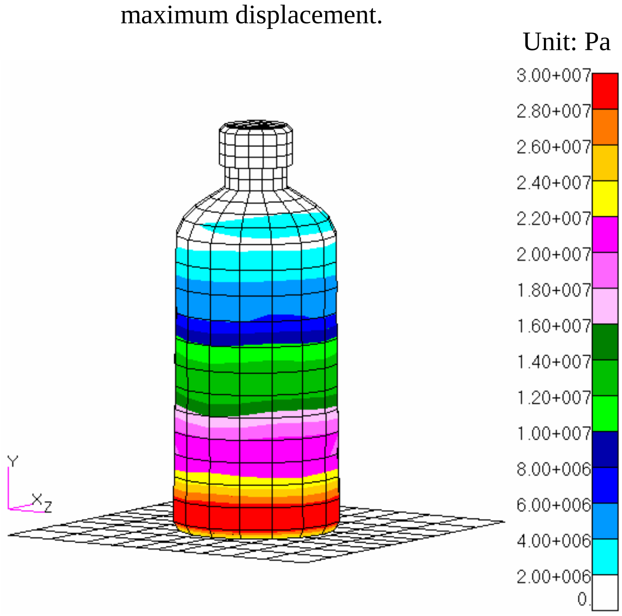


Figure 15. The drop-test of the General coupling model at maximum displacement.

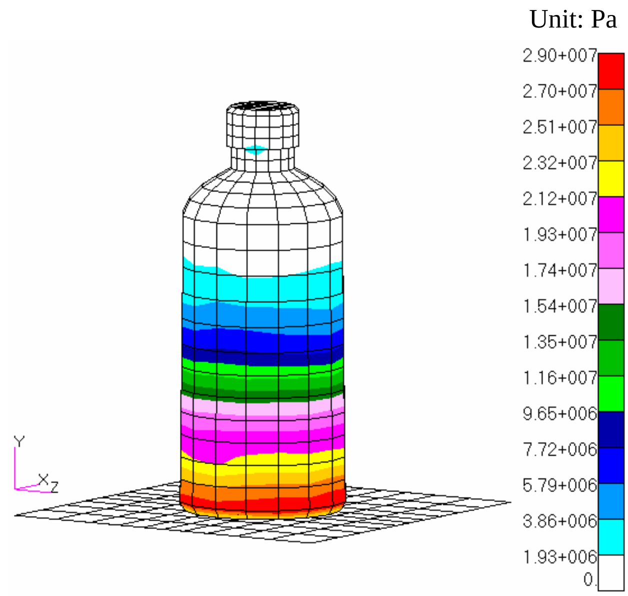


Figure 16. The drop-test of the ALE model at maximum displacement.

### 4.3 CPU time

The CPU time required for the different models was also considered. Using desktop PC (Pentium4-3.0GHz, 1.0 GB RAM), the required CPU time for 10 ms real-time simulation ranged from minimum of about 16:20 min for ALE model to a maximum time of about 35:33 min when the fluid was modeled with General coupling (Table 4). The CPU time of the General coupling required that are 2.10 and 2.18 time of magnitude higher than the Lagrangian and the ALE respectively. While, the CPU time of the Lagrangian nearly the ALE.

Table 4. Require CPU time for different fluid models

| No. | Numerical model of water | Require CPU time |
|---|---|---|
| (1) | Lagrangian | 16:55 min |
| (2) | General Coupling | 35:33 min |
| (3) | ALE | 16:20 min |

## 5. Conclusion

In this paper, three different numerical simulation models were used and compared with experimental data. The simulation revealed that the fluid-structure interaction when drop-test the bottle had a significant effect on the motion and structure response of the bottle. Mesh distortion appeared on drop-test the Lagrangian model at maximum displacement and the accuracy decreased due to highly distorted elements at the contact interface. To prevent high mesh distortion, simulations of structure by using Lagrangian solver and fluid by using Eulerian solver in the General coupling and ALE method had developed to compute coupling forces at the fluid-structure interface node.

The ALE approach can reduce the error from the mesh distortion but it has many steps to create the simulation model of the water-filled bottle.

The advantage of General coupling method is that, it is easy to create fluid filled into the bottle. However, the CPU time required for this method is much larger than those of other models. The General coupling model may be considered as the practical method for engineering application as it provides the appropriate structure behavior of plastic bottles during drop-test analysis.

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