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Analysis of Fluid-Structure Interaction Effects of Liquid-Filled Container under Drop Testing

Chakrit Suvanjumrat*, Tumrong Puttapitukporn and Satjarthip Thusneyapan

ABSTRACT

An analysis of drop-impact test for plastic containers is a first step toward the simulation of impact events for design and development purposes. Computer methods based on finite element analysis (FEA) were able to predict the performance of liquid-filled plastic containers to withstand drop-impact loading without rupture. This paper presented results of finite element analysis studied drop-test of liquid-filled plastic bottles. The aim of this study was to determine the accuracy of a non-linear explicit FE code in the MSC.Dytran program, by comparing FEA results to experiments. This paper is to lay down the effective procedures for analyzing the drop-test using FEA, which are appropriate for the design and development of plastic containers.

Key words: plastic container, drop test, fluid-structure interaction, FEA, explicit FE code

INTRODUCTION

Plastic containers are extensively used both domestically and industrially to handle liquid goods. Typical examples can be found in packaging, e.g. cans, drums, and bottles. The bottles are usually made from Polyethylene terephalate (PET) by the injection stretch blow molding process. These bottles are subjected to a drop impact test, which requires them to be filled with water and dropped onto hard steel or concrete bases to determine the height from which they can be dropped without rupture (D2463-95, 2001). The research originated from the fact that it was requirement from plastic container industries to determine the impact resistance of the liquid-filled plastic bottles. Effective tool for simulating the filled package makes it possible to achieve competitive and acceptable designs at lower cost. The MSC.Dytran program contains three-dimensional analysis code for solving problems involving contact dynamics and fluid-structure interaction (MSC.Dytran, 2005). But, to replace the physical test, it is required that drop test simulation supplies reliable results. Thus, it is challenging requirement to build up the simulation model properly, which includes the geometry simplification, FE models, material models, and boundary conditions.

In our studies, drop tests with the simple geometry bottles at various heights and volumes of filled water are initially experimented. Drop testing of the bottles can be conducted by dropping squarely onto the base is specified for the test. Impact force signals from repeating tests are recorded by the force plate. Secondary, the finite

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element method (FEM) is used to simulate the drop-test. Detail discussion is presented to imply the method properly. The pre-and post-processors of the MSC.Patran program is used to prepare and evaluate the MSC.Dytran results (MSC.Patran, 2005). The mean signals collected from the experimental are compared their accuracy to finite element results.

MATERIAL AND METHODS

EXPERIMENTAL

Experimental data from drop test was obtained by conducted bottles of cylindrical shape with 500 ml capacities. The bottles were partially filled with 250 and 500 ml of water, which weighted 284 and 510 grams respectively. 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 down, was specially constructed from AMTI model OR6-7. Its outputs were coupled to record the total impact force. Figure 1 shows the sample bottle and the force plate. In order to record the force pulse signals, the signals from the force plate were transmitted to amplifier, A/D converter, and hard disc in PC. Fifteen drops for each case were conducted to ensure the repeatability of testing results. The forced traces of vertical impact angle were chosen not to exceed ±3 degrees from vertical line. Pictures extracted from video recorder files are shown in Figures 2 and 3. These are the example of the half water-filled bottles released from the height of 0.5 m and the full water-filled bottles released from the height of 1.0 m. The sequences of falling bottle are shown in sequent time from (a) to (d). In these experiments, the force traces obtained from drop test; 1) the drop height 0.5 m of empty bottles, 2) the drop height 0.5, 1.0, and 1.5 m of the 250 ml of water filled bottles, and 3) the 500 ml of water filled bottles. All of these results are shown in Figures 4-10 respectively.

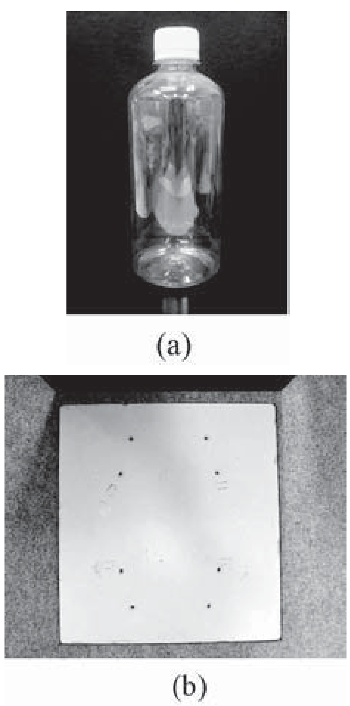

Figure 1 (a) Example of the bottle and (b) The AMTI force plate model OR6-7.

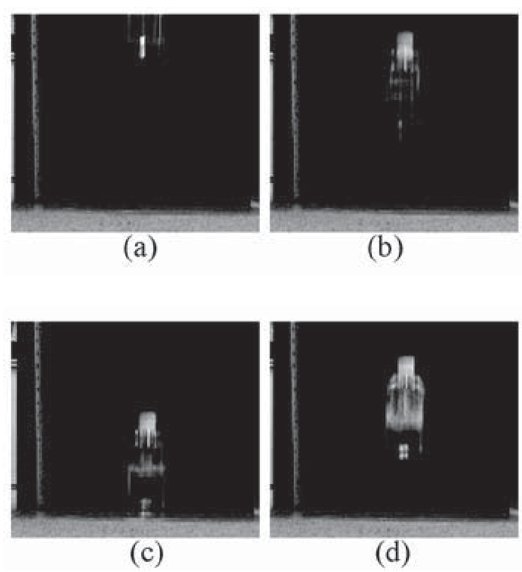

Figure 2 The drop test experiment of half water-filled bottle from 0.5 meter height.

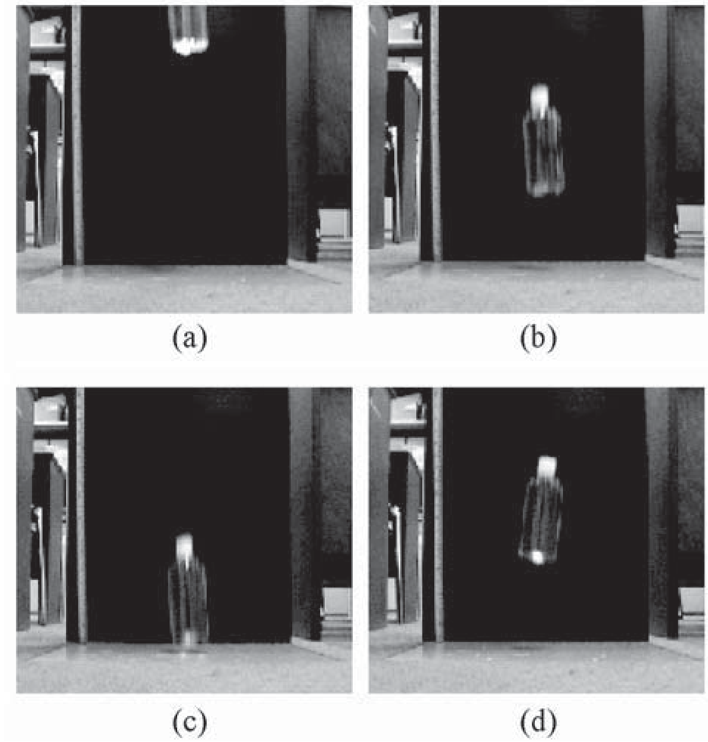

Figure 3 The drop test experiment of full water-filled bottle from 1.0 meter height shows in sequent from (a) to (d).

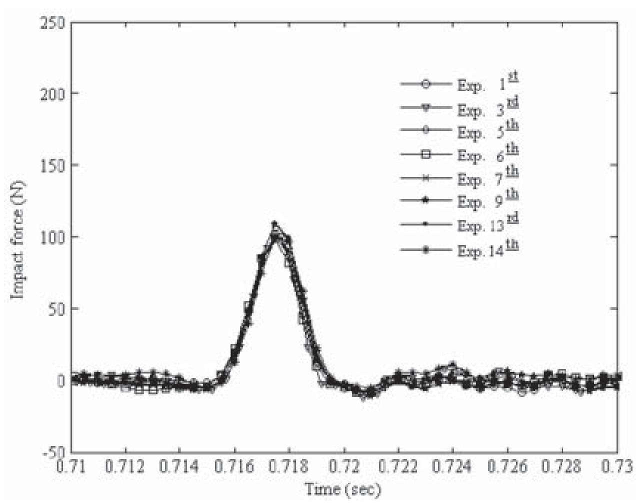

Figure 4 Force traces of the drop test of empty bottles from 0.5 meter height.

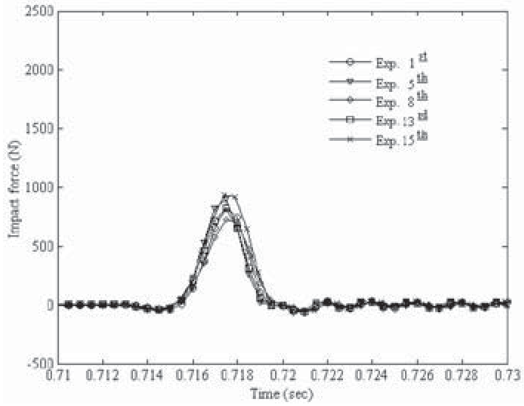

Figure 5 Force traces of the drop test of half water-filled bottles from 0.5 meter height.

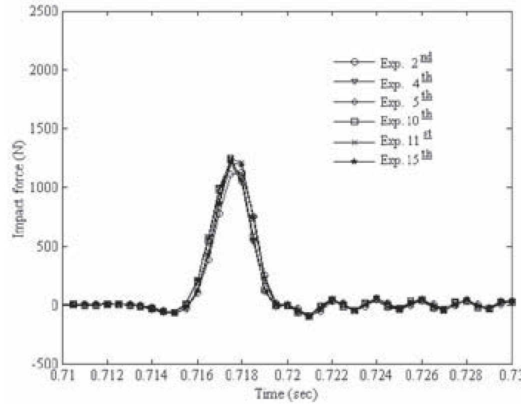

Figure 6 Force traces of the drop test of half water-filled bottles from 1.0 meter height.

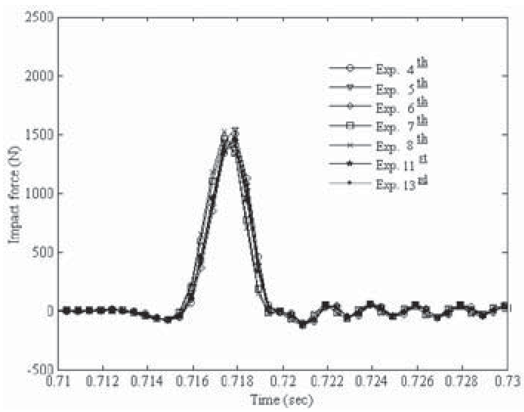

Figure 7 Force traces of the drop test of half water-filled bottles from 1.5 meter height.

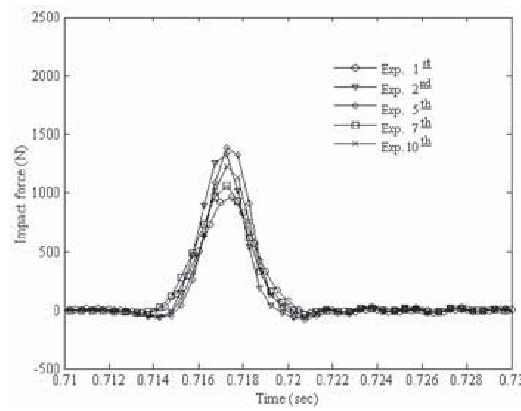

Figure 8 Force traces of the drop test of full water-filled bottles from 0.5 meter height.

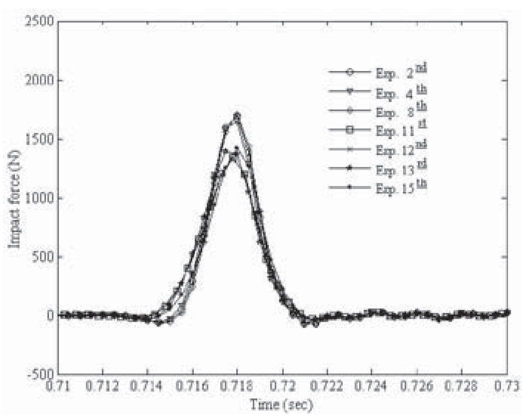

Figure 9 Force traces of the drop test of full water-filled bottles from 1.0 meter height.

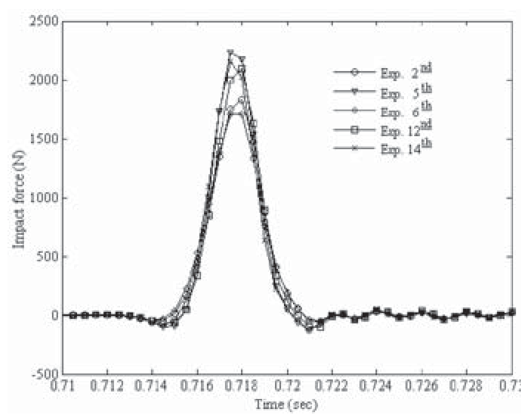

Figure 10 Force traces of the drop test of full water-filled bottles from 1.5 meter height.

Simulation methodology

The 3D finite element code in the MSC.Dytran program, which is suitable for the transient non-linear solver, was used in our analyses. MSC.Dytran is a finite element explicit time integration code for dynamic analyses, which allows us using both Lagrangian and Eulerian algorithms in modeling structures and fluids. Shell, beam, plate, and solid elements can be used by the Lagrangian solver, while only solid elements are available for the Eulerian solver. The mesh in the Lagrangian solver consists of grid points and constant mass elements on the body. Grid points can move in space following the elements deformation while the body is deformed. The governing equations of motion are

$$[M]\{\ddot{D}\}+[C]\{\dot{D}\}+[K]\{D\} = \{f_{ext}\} \quad (1)$$

or

$$[M]\{\ddot{D}\} + \{f_{int}\} = \{f_{ext}\} \quad (2)$$

where [M], [C], [K] and are the mass, damping, and stiffness matrices respectively. $\{F_{ext}\}$ is the external load vector. $\{F_{int}\}$ is the internal load vector. $\{D\}$, $\{\dot{D}\}$ and $\{\ddot{D}\}$ are the displacement, velocity, and acceleration vectors respectively. The above set of equations is fully decoupled for each degree of freedom via lumping process of mass matrix, [M]. The acceleration at the time step *n* is directly obtained as

$$\{\ddot{D}\}_n = [M]^{-1}(\{f_{ext}\}_n - \{f_{int}\}_n) \quad (3)$$

thus avoiding any matrix decomposition. To perform the time integration, the central difference scheme is adopted by assuming a constant time step. However, an explicit integration method is conditionally stable. It requires for a valid solution in which the time step must be smaller than a critical value given by the condition

$$Ot \; A \; Ot_{cr} = \frac{Tn}{\Theta} \quad (4)$$

where T_n is the smallest time period of the finite element related to the finite element system with *n* degree of freedom.

The Eulerian processor evaluates the motion (flow) of the material through the mesh of constant volume elements. The governing equations are called Euler equations for the fluid, which express the mass, momentum and energy conservation.

$$\frac{Eq}{Et} + \frac{Ef(q)}{Ex} + \frac{Eg(q)}{Ey} + \frac{Eh(q)}{Ez} = 0 \quad (5)$$

where q is the state vector. f(q), g(q) and h(q) represent the fluxes of the conserved state variables. In a typical impact simulation, there are air, water, and plastic of bottles. The air is assumed to be an ideal gas and satisfied the equation of state

$$p = (\Im\text{-}1) \Leftarrow e \quad (6)$$

where p, $\Leftarrow$ and e are the pressure, density, and specific internal energy, respectively. $\Im$ is the ratio of the heat capacities of the gas. The equation of state of water is assumed to be in the form of

$$p = \left(\frac{\rho}{\rho_0} - 1\right) \quad (7)$$

where p, $\Leftarrow$ and $\Leftarrow_0$ are the pressure, density, reference density, and bulk modulus respectively. In this study, MSC.Dytran was used as the solver in each simulation. MSC.Patran was used for pre- and post-data processing.

Empty bottle modeling

The model consists of the shell of the bottles and the shell of the force plate as shown in Figure 11.

The bottle model used in the present work was constructed from 998 quadratic shell elements. The force plate model was constructed from 100 shell elements and placed under bottle model at the location -0.01 m in y-direction.

Fluid-filled bottle modeling

To allow interacting between structure and fluid in MSC.Dytran, general coupling algorithm on the surface of the bottle was used. This acts as boundary condition to the flow of the material in the Eulerian mesh. During one time step within the explicit method, this boundary is calculated after the new positions of the grid points are known. Thus, it can be seen as a stationary or moving wall. This methodology was placing the empty model into the fluid models which used solid element as shown in Figure 12. The fluid model used in the present work was constructed from 1,300 rectangular solid elements.

The basic of general coupling algorithm is the 2D case as shown in Figure 13. Figure 13a shows empty bottle and force plate model. Figure 13b shows the empty bottle into the space of fluid element. In Figure 13c, we used the bottle surface as the volume to generate a new control volume in the Eulerian solver. By this approach, the advantage of the general coupling surface can undergo arbitrarily in motions and can be of any shape as long as it has a closed volume (Suvanjumrat *et al*., 2007a).

Materials

Material models of the bottle used the piecewise linear plasticity (DMAT24) in MSC.Dytran. This model presented an elastic-plastic material and required true stress/strain data (D882-02, 2002 and D638-03, 2003). This data was collected from tensile test (Suvanjumrat *et al*., 2007b). The material properties of the bottles were

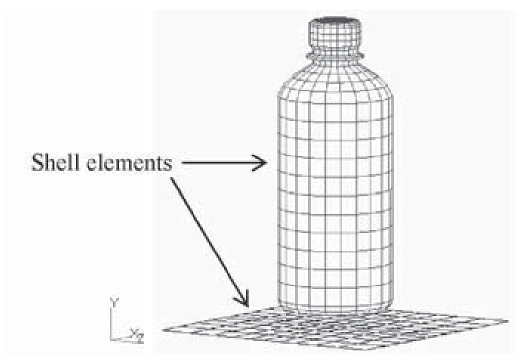

Figure 11 The bottle and force plate models.

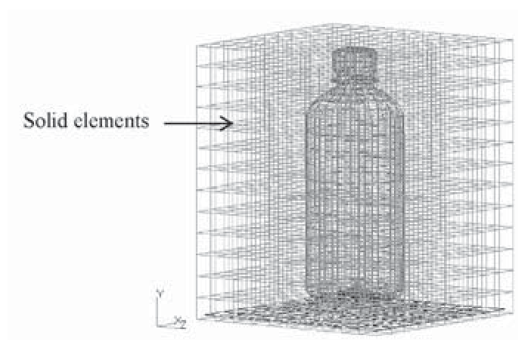

Figure 12 The fluid models.

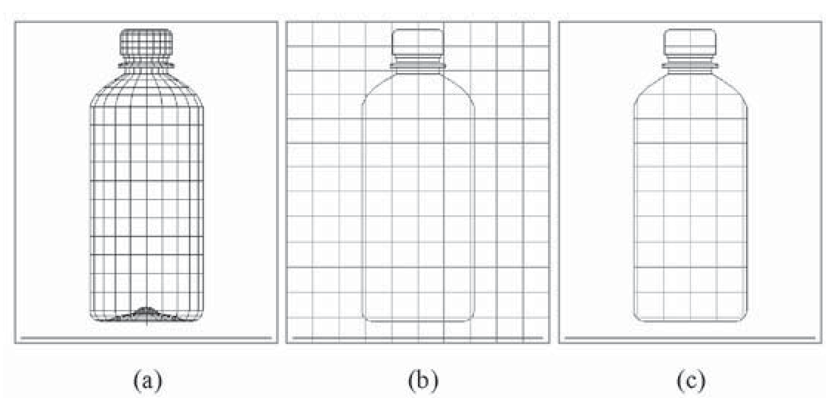

Figure 13 Change control volume due to the coupling surface.

modulus of elasticity E = 888.41 MPa and Poissons ratio $\downarrow$= 0.49. The elastic-plastic material properties were impremented as a function of strain rates (Suvanjumrat *et al*., 2007b). The material model of force plate was used as rigid material (MATRIG).

The density of water was 997 kg/m^3. The density of air was 1.1855 kg/m^3 at 25 °C (Cengel and Boles, 2006). To model the fluid inside of the bottle, we separated it with the single material and the multiple materials. In the single material (used for a full water-filled bottle), we defined air as solid elements for an empty bottle and water as solid element as shown in Figure 14a. In the multiple materials (used for the partly-filled water), the water and air regions were subdivided into Eulerian two solid elements and the interface boundary between the water and air elements existing only at the beginning of the analysis as shown in Figure 14b. The outside of every case on the bottle surface is no material in order to save computation time.

Contact algorithm

The contact algorithm is suitable for a problem of the impact between a moving object (bottle) and a rigid station wall (force plate). The impact force, stress, and deformation resulting from this impact can be obtained from the analysis. The contact interface can be defined by a set of two geometry surface, which may come into contact during a transformation. Here, contact is represent using the classical "master-slave" technique. Associated with the penalty method, this representation expresses impenetrability of the slave nodes into the elements of the master surface as shown in Figure 15.

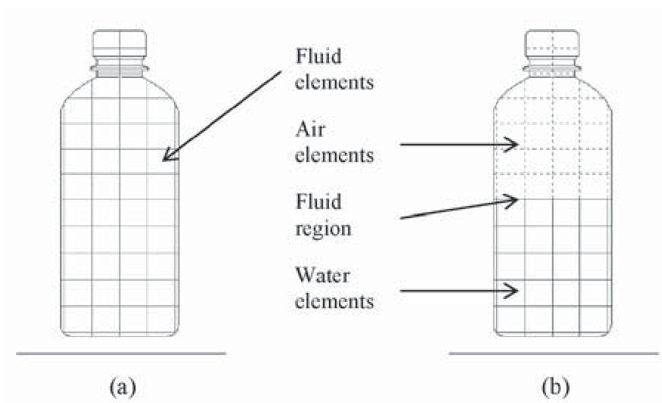

Figure 14 (a) The full fluid-filled bottle and (b) The partially fluid-filled bottle.

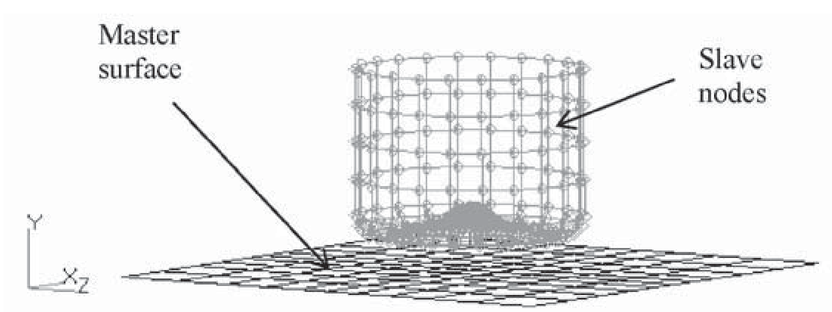

Figure 15 The concept of master surface and slave nodes.

From the equilibrium equation (2), the contact condition is expressed by penalizing the interpenetration of the surface in contact, which leads to the adjunction of a reaction force (F_{cont}) into the right-hand side of the discretized equation.

$$[M]\{\ddot{D}\}+\{F_{int}\} = \{F_{ext}\}\{F_{cont}\} \qquad (8)$$

Initial condition

In order to save computational time, the simulation of the drop test of the bottle had been started at location 0.01 m drop height above the force plate. At this time, the initial body velocity had been assumed as

$$v_i = \sqrt{2gh} \qquad (9)$$

$$\text{with} \quad h = d - g \qquad (10)$$

where d is the nominal drop height and g is gap between bottle base and force plate. This implies no air gap existing in the bottle above the force plate.

The same position of the bottle model was used for all simulation but the initial velocity according to drop height following the above equation.

RESULTS AND DISCUSSION

The comparatives of the simulation results will be presented and discussed in accordance with the experimental data collected as discussed in the previous section. In case 1 (the empty bottle at 0.5 m drop height), the comparisons between experimental and FEA is shown in Figure 16. In case 2 (the half water-filled bottles with drop height of 0.5, 1.0, and 1.5 m), the comparisons between experimental and FEA are shown in Figures 17-19. In case 3 (the full water-filled bottles at 0.5, 1.0, and 1.5 m height), the comparisons between experimental and FEA are shown in Figures 20-22 respectively. The contour plot of von misses stress on the wall of the bottle in case 3 (at 1.0 m drop height) displays in sequential time from (a) to (d) as shown in Figure 23.

In this investigation, the magnitudes of impact forces were increased by increasing amount of filled water in the bottle. Figure 24 shows the magnitude of impact force compared between the half and full water-filled for the experimental. The magnitudes of impact forces was increased 33.16 % by average. Figure 25 and 26 show the

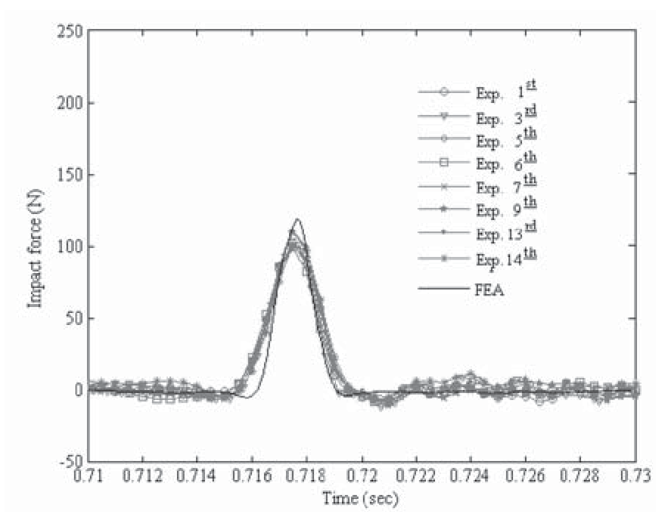

Figure 16 Force traces of the drop test of empty bottles from 0.5 meter height comparing between experiments and FEA.

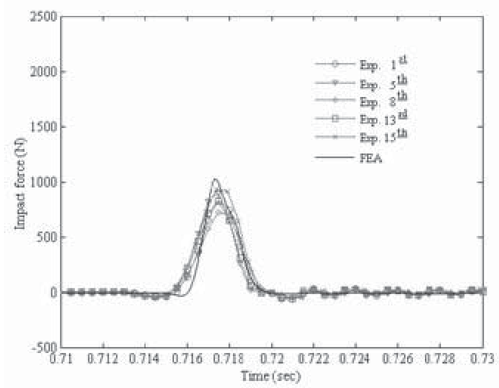

Figure 17 Force traces of the drop test of half water-filled bottles from 0.5 meter height comparing FEA with experiment.

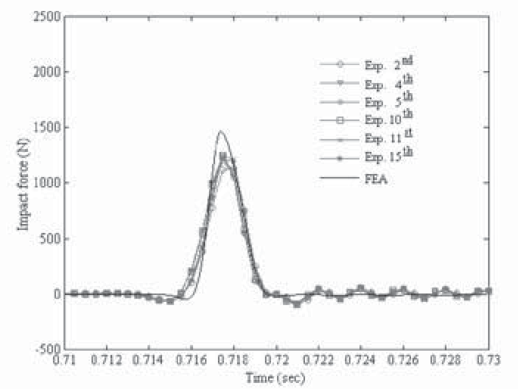

Figure 18 Force traces of the drop test of half water-filled bottles from 1.0 meter height comparing FEA with experiment.

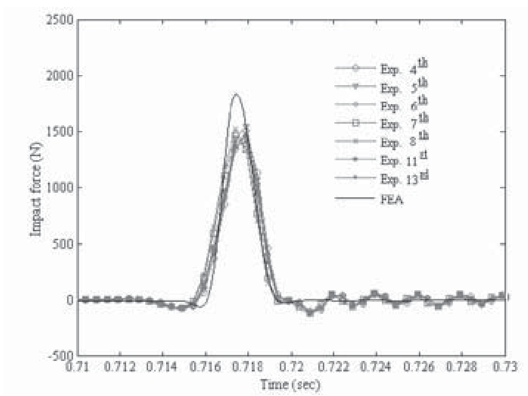

Figure 19 Force traces of the drop test of half water-filled bottles from 1.5 meter height comparing FEA with experiment.

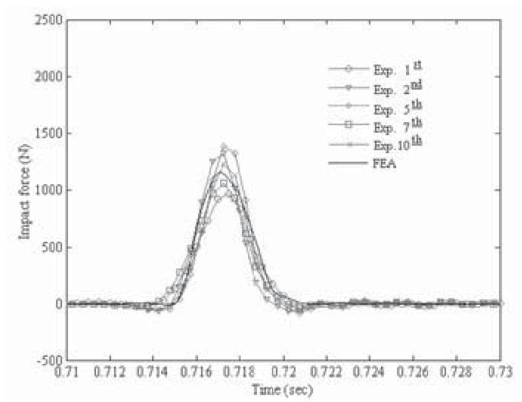

Figure 20 Force traces of the drop test of full water-filled bottles from 0.5 meter height comparing FEA with experiment.

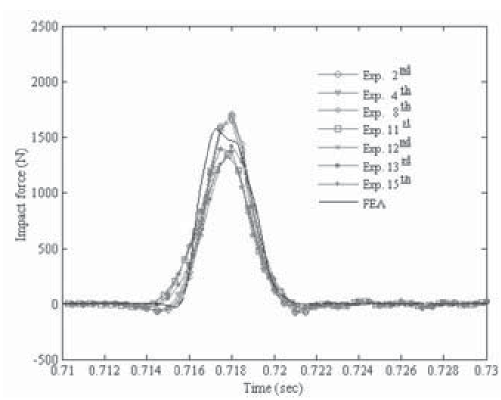

Figure 21 Force traces of the drop test of full water-filled bottles from 1.0 meter height comparing FEA with experiment.

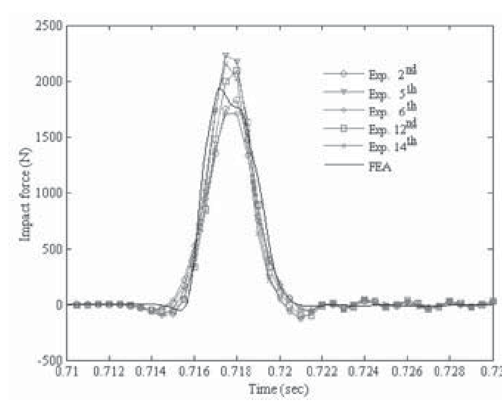

Figure 22 Force traces of the drop test of full water-filled bottles from 1.5 meter height comparing FEA with experiment.

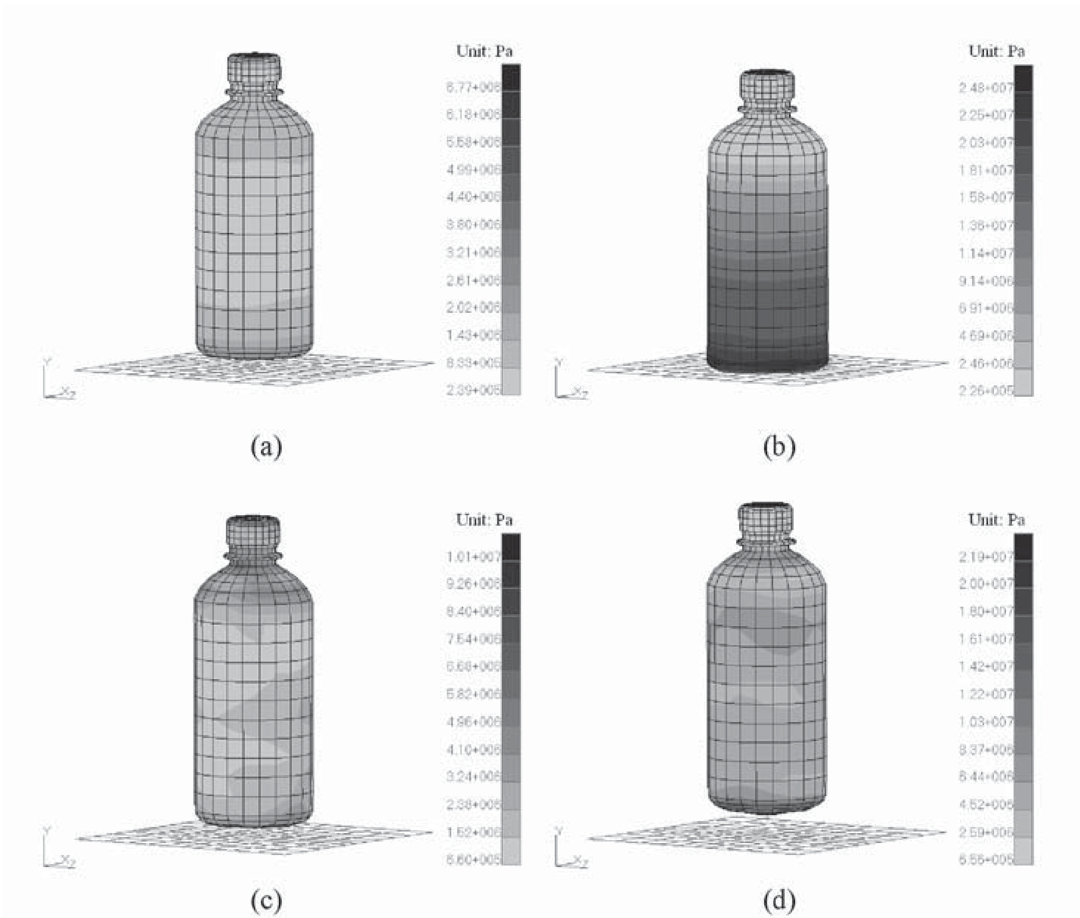

Figure 23 The contour plot of von misses stress obtained from case III (1.0 m drop height) in sequent from (a) to (d) of the full water-filled bottle.

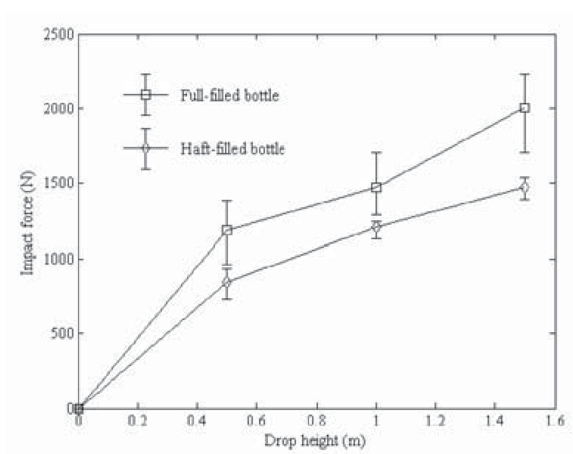

Figure 24 The comparative of impact force between the drop test of half and full water-filled bottles from 0.5 to 1.5 meter height.

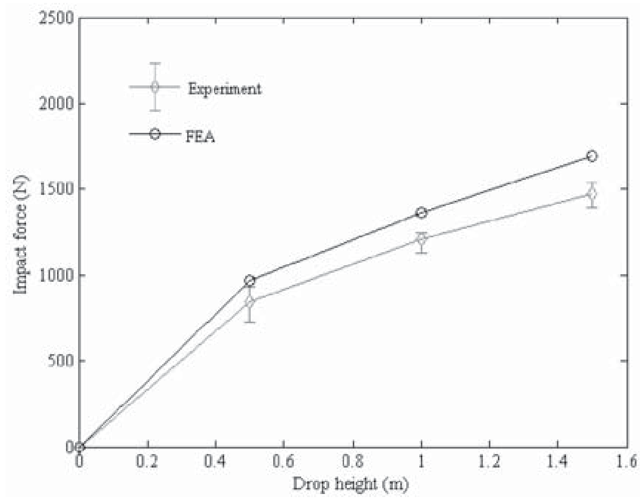

Figure 25 The drop impact force of half water-filled bottles from 0.5 to 1.5 meter height comparing FEA with experiment.

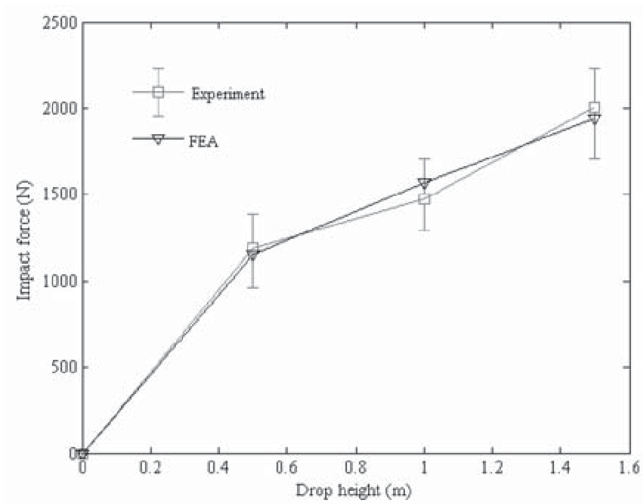

Figure 26 The drop impact force of full water-filled bottles from 0.5 to 1.5 meter height comparing FEA with experiment.

comparison between simulation and experiment at each drop height for case 2 and 3 respectively. The first peak of impact forces of simulation agrees with the experimental. The errors of the average impact forces are 14.7, 12.5, and 4.2 % for case 1, 2, and 3 respectively.

CONCLUSIONS

The modeling and simulation methods for drop test of plastic bottles have been discussed in detail. The emphases are on how to get reliable results using effective modeling techniques. The realistic cases were used to verify our FEA.

Comparing the simulation results with experimental data, the good agreement was observed. The practical successes were shown that the drop test could be simulated in order to evaluate the current design and could be a guide for design improvement. A change at design stage could make relatively easier. Thus, the iterative simulation for the modified models could develop an optimal design. Consequently, it could reduce the number of required physical tests and could make shorter time for the product-to-market results.

This work presented the application of the FEM concerning with two solvers. Of the three cases of the drop test discussed in this paper, the third case obtained the most accurate result for analyzing the impact event. Quantitatively, the obtained results showed a good agreement with the experimental data. This FEM could be a practical tool in the containers design.

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