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Determination of Drop-Impact Resistance of Plastic Bottles using Computer Aided Engineering

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ABSTRACT

ASTM D2463 discusses the standard test method for drop impact resistance of blow-molded thermoplastic containers using procedures to determine the mean failure height and the standard deviation of the distribution. Unfortunately, costly prototypes have to be created before the drop impact test can be conducted. The MSC Dytran program was used with finite element simulation of the drop impact test of plastic bottles to determine the failure height for polyethylene terephthalate (PET) and high density polyethylene (HDPE) bottles. The finite element results were verified using experimental results obtained using the test method prescribed in ASTM D2463. It was found that the finite element simulation obtained accurate results. The failure heights for the PET and HDPE bottles were 4.53 ± 0.41 m and 4.65 ± 0.81 m, respectively. The errors in the failure height obtained from the FE simulation were less than 9.27% for the PET bottle and 5.59% for the HDPE bottle.

Keywords: drop test, impact resistance, failure height, finite element, plastic bottle

INTRODUCTION

During the preliminary design period of plastic bottles, the drop impact test is one of the customer's requirements. In ASTM D2463-95 (2001), drop testing of the plastic bottles can be conducted by completely filling a bottle with water and dropping it onto the floor. The objectives for the drop impact test are to control the bottle's qualities and also to determine the mean failure height. Many efforts have been made to perform computer simulation of the drop impact test of plastic bottles to determine their impact strength. Reed *et al*. (2000) proposed a mass-spring model for determining loads which is an input to finite element modeling (FEM) of the drop impact test of bottles. Masood *et al*. (2005) used the Pro/Mechanica finite element program for developing polyethylene terephthalate (PET) water fountain bottles. However, these research projects used only finite element analysis (FEA) to solve the drop impact test of plastic bottles, which must take into account the effects of fluid sloshing inside the bottle and the interaction between fluid flow and bottle structure. Not only does the simulation of the drop impact test of plastic bottles use FEA, but it is also concerned with using computational fluid dynamics (CFD) to simulate the fluid models affecting the inside wall of the bottles. Recent research (Suvanjumrat *et al*., 2007, 2008) proposed fluid-structure interaction (FSI) algorithms for simulating the drop impact test of PET plastic bottles implemented into the MSC Dytran program. The bottle structure was simulated using

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the FEA method, while the CFD method was used to simulate the moving water inside the bottle. The FSI of a fluid-filled container has been studied earlier (Anghileri *et al.*, 2005; Karac and Ivankovic, 2009; Yuan and Xianlong, 2010), but none of these studied the failure of the structure made from a plastic material. In the current research, the material properties at failure of plastic bottles made from PET and high density polyethylene (HDPE) were studied and the criterion to determine the failure height of these plastic containers was proposed. This research could present a fundamental procedure for the design of plastic bottles under the ASTM standards for the drop impact test.

MATERIALS AND METHODS

Determination of failure criterion

In a previous study (Suvanjumrat *et al.*, 2007) of PET liquid containers, after the onset of yielding by the PET containers, the proposed mathematical model of the flow stress was sown to be a function of both plastic strains and strain rates as shown in Equation 1:

$$\sigma(\varepsilon_p,\dot{\varepsilon})=A(1+B\varepsilon_p)(1+B\varepsilon_p^n)\left[1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{m}}\right] \quad (1)$$

where ε_p is plastic strain; $\dot{\varepsilon}$ is strain rate; A, B, C, m and n are constants.

The flow stress model was implemented in the finite element models of the PET bottles to simulate the drop impact test (Suvanjumrat *et al.*, 2008). The simulation results of impact forces showed a good correlation with the experiments, but the failure height of the PET bottles could not be determined.

In the current research, the failure criterion of plastic bottles was studied to determine their failure heights under the drop impact test. The cross-section area of the polymer specimens was reduced to the limited stain by the tensile failure (Xinran, 2008). Thus, the failure criterion was proposed as Equation 2:

$$\sigma \geq \sigma_f \quad (2)$$

where σ_f is the failure stress (Thiruppukuzhi and Sun, 2001) at the limited strain.

The tensile tests of PET and HDPE specimens were prepared according to ASTM D638-99 (2000) and ASTM D882-02 (2002), respectively. The material properties of these specimens revealed that the failure stresses of these plastic materials are inversely proportional to the strain rate. The failure stress decreases while the strain rate increases. Thus, this proposed failure criterion, the failure stress, σ_f can be written as Equation 3:

$$\sigma_f = De^{E\dot{\varepsilon}} + F \quad (3)$$

where D, E and F are constants.

In Equation 3, these constants are determined by the curve fitting method of the data obtained from tensile tests. For PET plastics, D, E and F are 95.7 MPa, -11.63 and 119 MPa, respectively. Figure 1 shows the plot of the failure stresses (σ_f) versus the strain rates of the PET specimens. For HDPE plastics, D, E and F are 180.58 MPa, 22.38 and 21.50 MPa, respectively. The plot of failure stresses (σ_f) versus the strain rates of the HDPE specimens is shown in Figure 2.

Experiment of the drop impact test

The mean failure heights of the plastic bottles were determined using the “Up and Down” or the “Bruceton Staircase” method referred to in ASTM D2463-95 (2001). The PET bottles had a cylindrical shape and 510 mL capacity, while the HDPE bottles had a capacity of 1 L as shown in Figures 3 and 4, respectively. Twenty PET and HDPE bottles were fully filled with water. The first PET bottle was dropped from a height of 3.0 m and the HDPE bottles from a height of 4.0 m, where the bottle was dropped so that there was vertical impact with the floor. The height of the drop impact test for the next bottle was increased by 0.5 m when the previous bottle did not fail on dropping. Otherwise, if the previous bottle had failed, the next bottle was dropped from a height that was lower by 0.5 m.

The mean failure height, h_f, and the standard deviation, s_f, obtained from ASTM D2463-95, (2001) can be written using Equations 4-7:

$$h_f = h_0 + d[(A / N) \pm 0.5] \quad (4)$$

where $$A = \sum_{i=0}^{i-k} In_i \quad (5)$$

$$s_f = 1.620d\frac{NB-A^2}{N^2}+0.029 \quad (6)$$

where $$B = \sum_{i=0}^{i-k} I^2 n_i \quad (7)$$

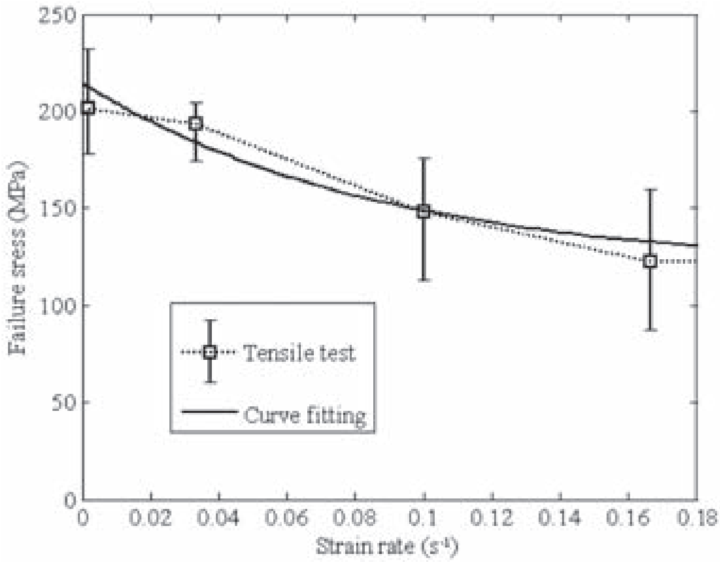

Figure 1 Plot of failure stresses, σ_f versus strain rates of PET specimens.(Vertical bars shown ± SD).

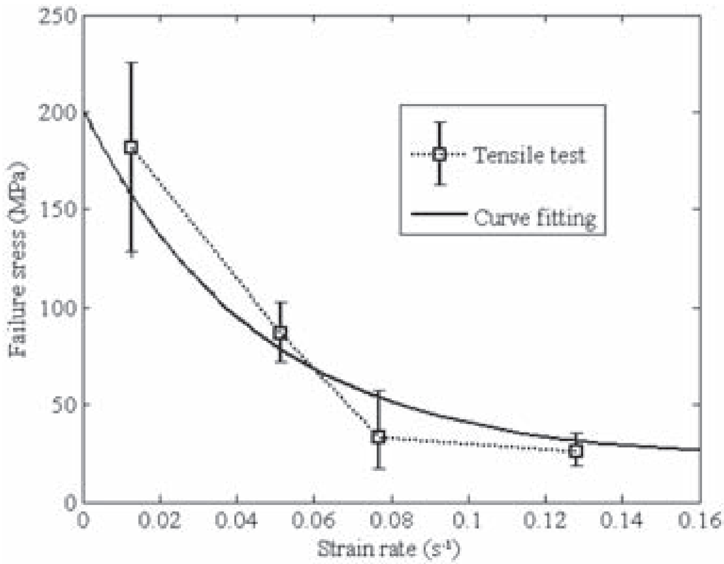

Figure 2 Plot of failure stresses, σ_f versus strain rates of the HDPE specimens. (Vertical bars shown ± SD).

where h_0 is the initial drop height; d is the increment in drop height; n is the number of failures or non-failures, whichever is pertinent at the level of I; k is the level of the drop height; and N is number of failures or non-failures, whichever is less.

Computational modeling

The finite element (FE) models of the drop impact test of plastic bottles were established based on the physical test in the MSC Dytran program. The models comprised a rigid floor, a deformable bottle and water. The FE models of both plastic bottles are shown in Figure 5.

Figure 3 Sample of test polyethylene terephthalate (PET) bottle.

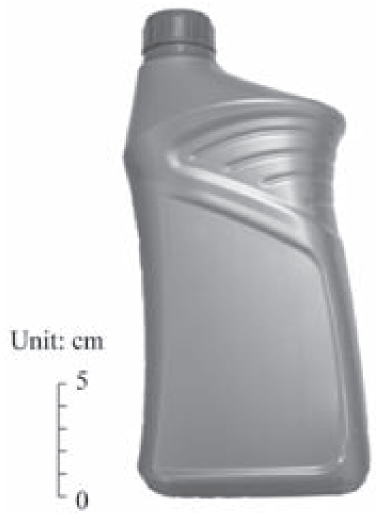

Figure 4 Sample of test high density polyethylene (HDPE) bottle.

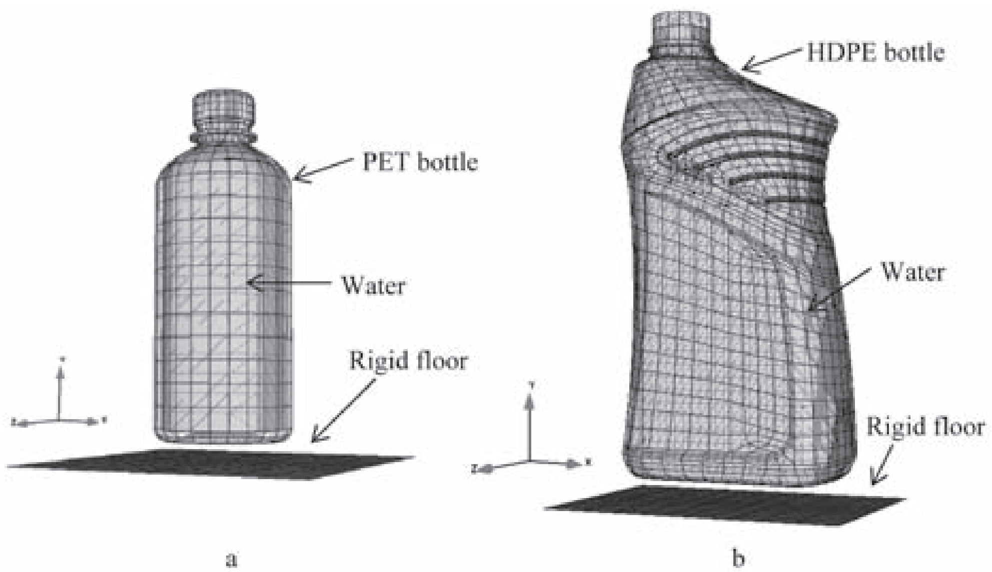

Figure 5 FE models of the water-filled bottles in the MSC Patran program: (a) polyethylene terephthalate (PET); and (b) high density polyethylene (HDPE).

Both models of the PET and HDPE bottles were precisely meshed in the MSC Patran program. Most elements were quadrilateral shell elements in which the ratio of the element length to the element width was less than 5 and their corner angles were within 45°–125°. The others elements were triangular elements, where their corner angles were 30°–85°. The thicknesses of the bottle models were calculated and their weights were compared to the average weight of the test samples. The results indicated the modeling thicknesses of the PET and HDPE bottles were 0.56 mm and 0.87 mm, respectively.

The flow stress of plastic materials can be written as Equation 8:

$$\sigma = \begin{cases} E\varepsilon_e & , \sigma \le \sigma_y \\ \sigma(\varepsilon_p, \dot{\varepsilon}) & , \sigma > \sigma_y \end{cases} \quad (8)$$

where E is the elastic modulus; ε_e is elastic strain; ε_p is plastic strain; σ_y is the yield stress. The material properties of plastics given in Equation 8 are listed in Table 1. The parameters of flow stress, $\sigma(\varepsilon_p, \dot{\varepsilon})$, are listed in Table 2.

The density of water was set at 998 kg.m^{-3} with a bulk modulus of 2.20 GPa. The elements of water were put into the FE bottle models using coupling techniques described in Suvanjumrat *et al*. (2008).

The FE simulations of the drop impact test of the PET bottles consisted of six drop heights (3.0, 3.5, 4.0, 4.25, 4.5 and 5.0 m). The FE simulations of the drop impact test of the HDPE plastic bottles consisted of five drop heights (4.0, 4.5, 5.0, 5.5 and 6.0 m). To expedite the computational time, all simulations were performed when the bottles were at a height of 0.01 m above a rigid floor where the corresponding velocities of the prescribed bottles were calculated. The initial velocities of the PET bottles were 7.65, 8.27, 8.85, 9.12, 9.38 and 9.89 m.s^{-1}, respectively. The initial velocities of the HDPE bottles were 8.85, 9.38, 9.89, 10.39 and 10.85 m.s^{-1}, respectively.

RESULTS AND DISCUSSION

Experimental results

The experimental results using the Bruceton Staircase procedure for the drop impact test of the PET bottles are shown in Table 3. Figure 6 shows the ruptures found on the bottom of bottles.

The experimental results of the drop impact test of the HDPE bottles are shown in Table 4. Figure 7 shows ruptures of the HDPE bottles found on the side corner of the bottles.

Table 1 Mechanical properties of plastic materials of the tensile tests.

Materials	Density ρ (kg.m^{-3})	Elastic modulus E (MPa)	Poission ratio v	Yield stress σ_y (MPa)
PET	1,288.79	888.41	0.36	26.49
HDPE	839.00	636.49	0.38	16.45

Table 2 Flow stress parameters of plastic materials by the curve fitting method of data obtained from tensile tests.

Material	A	B	C	m	N
PET	7.59×10^6	0.25	0.1005	0.46	2
HDPE	16.01×10^6	0.25	1.9287	1	2

Table 3 Bruceton Staircase drop impact test result of PET plastic bottles.

Drop height (m)	Outcome of test (X = failure, O = non-failure)																				n_X	n_O	I	n_i	In_i	I^2n_i
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20						
3.0	O																				0	1	-	-	-	-
3.5		O		O																	0	2	-	-	-	-
4.0			X		O												O				1	2	0	1	0	-
4.5						O		O		O		O		O		X		O		X	2	6	1	2	2	-
5.0							X		X		X		X		X				X		6	0	2	6	12	24
																				Totals	9	11	-	9(N)	14(A)	26(B)

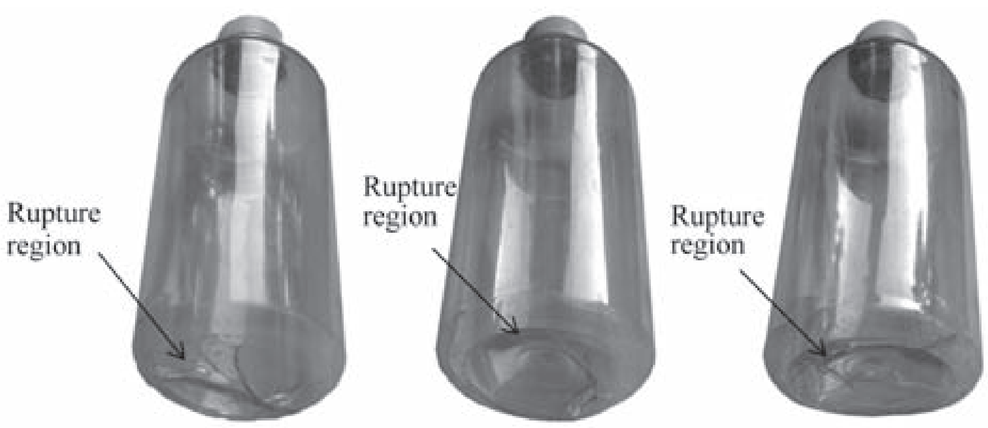

Figure 6 Ruptures found on the bottom of the PET bottles after the drop impact test.

Table 4 Bruceton Staircase drop impact test result of HDPE bottles.

Drop height (m)	Outcome of test (X = failure, O = non-failure)																				n_X	n_O	I	n_i	In_i	I^2n_i
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20						
4.0	O						O								O		O		O		0	5	-	-	-	-
4.5		O		O		X		O						X		X		X		X	5	3	0	5	0	0
5.0			X		X				O				X								3	1	1	3	3	3
5.5										O		X									1	1	2	1	2	4
6.0											X										1	0	3	1	3	9
																				Totals	10	10	-	10(N)	8(A)	16(B)

Figure 7 Ruptures found on the side of the HDPE bottles after the drop impact test.

The mean failure height ± standard deviation of the drop impact test was calculated using Equations 4–7. The failure heights for the PET and HDPE bottles were 4.53 ± 0.41 m and 4.65 ± 0.81 m, respectively.

Simulation results

The maximum Von Mises stress in the FE simulations for the drop impact test of the PET bottle is shown in Figure 8. During impact, the Von Mises stress was concentrated near the bottom of the PET bottle, where the water hammer occurred. As the PET bottle rebounded, the column of water hit the bottom of the PET bottle, where the maximum Von Mises stress was detected. The maximum Von Mises stress increased as the drop height increased. For all drop heights of the PET bottles, the maximum Von Mises stresses were found on the bottom of the PET bottles. Where bottle failure occurred, the maximum Von Mises stress exceeded the stress defined in the proposed failure criterion. These maximum Von Mises stresses and strain rates were plotted in a graph (Figure 1) to determine the failure height. In Figure 9, the predicted failure height is shown at the intersection of the curve of the proposed failure criterion and a curve fitted by the maximum Von Mises stresses and strain rates, at a height of 4.11 m (within the range of the failure height of 4.53 ± 0.41 m). In the FE simulation, the failure height had an error of less than 9.27% compared to the mean failure height given by the Bruceton Staircase method.

The maximum Von Mises stress during impact of the HDPE bottle with the rigid floor is shown in Figure 10. The Von Mises stress was concentrated on the wall near the bottom of the HDPE bottle. While the HDPE bottle did not rebound, the wall of the bottle was circumferentially expanded by the water. Consequently, the maximum Von Mises stress concentration occurred on the wall edge of the HDEP bottle. The maximum Von Mises stress increased as the drop height increased. For all drop heights of the HDPE bottles, the maximum Von Mises stresses were found on the wall edge. In the case of bottle failure, the maximum Von Mises stress exceeded the stress defined by the proposed failure criterion. These maximum Von Mises stresses and strain rates were plotted in a graph (Figure 2) to determine the failure height. In Figure 11, using a similar method to that for the PET bottles, the predicted failure height was found at the intersection of the curve of the proposed failure

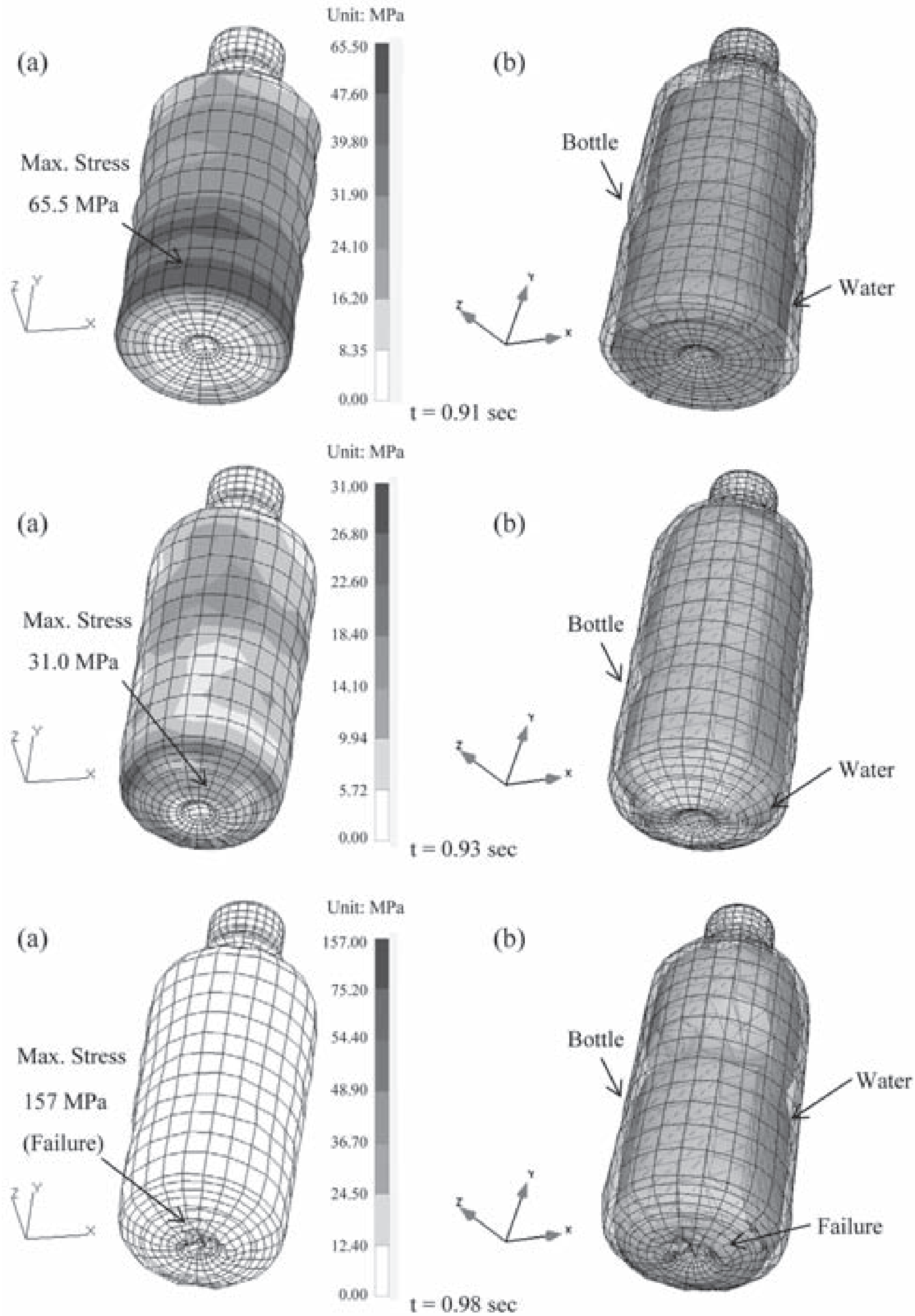

Figure 8 Simulation results: (a) Von Mises stress on the bottle surface; and (b) movement of water inside the PET bottle during impact and rebound on the floor at a drop height of 4.25 m.

criterion and a curve fitted by the maximum Von Mises stresses and strain rates, at 4.91 m (within the range of the failure height of 4.65 ± 0.81 m). In the FE simulation, the prediction of the failure height had an error of less than 5.59% compared to the mean failure height given in the Bruceton Staircase method.

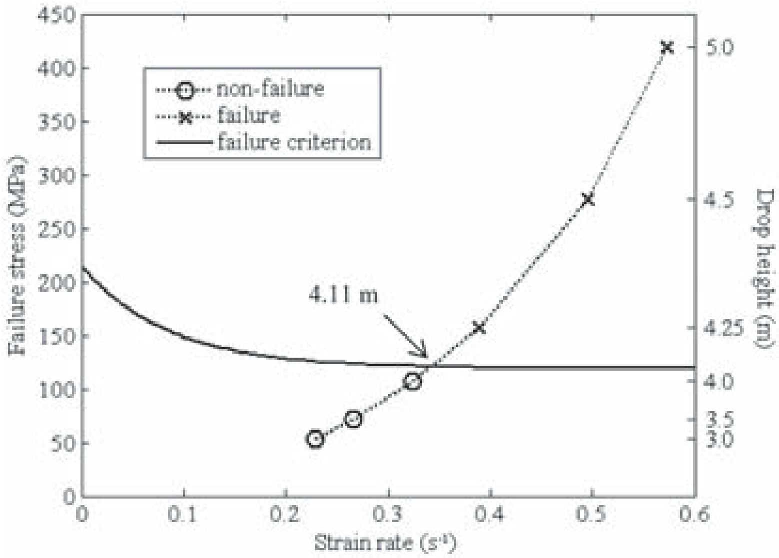

Figure 9 Proposed failure criterion used to determine the failure height of the PET bottle.

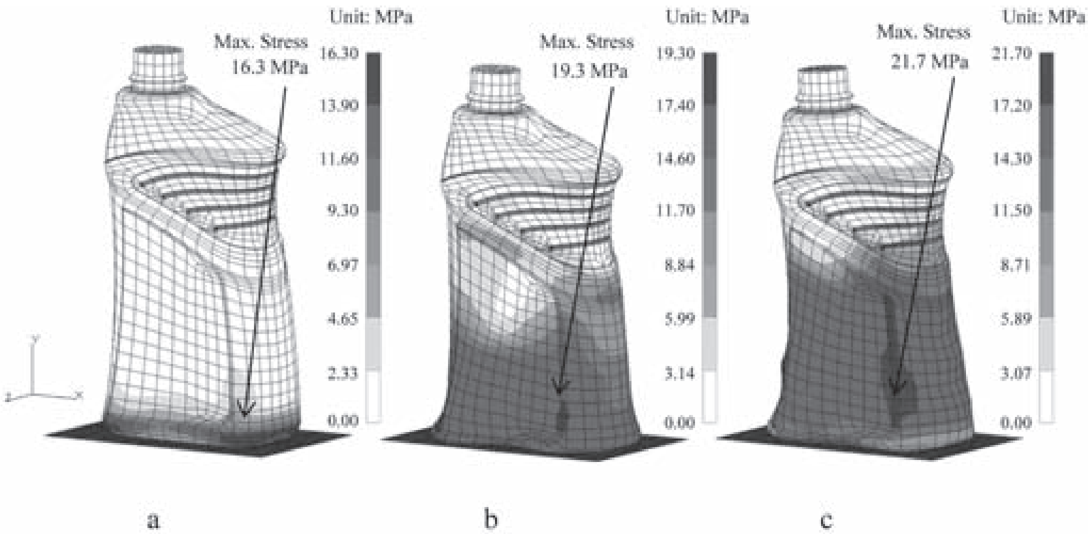

Figure 10 Simulation results of the Von Mises stress distribution on the wall of the HDPE bottle at the drop height of 5.0 m at: (a) t = 1.008 sec; (b) t = 1.01 sec; and (c) t = 1.012 sec. Stress concentrates at the wall edge of the HDPE bottle during impact.

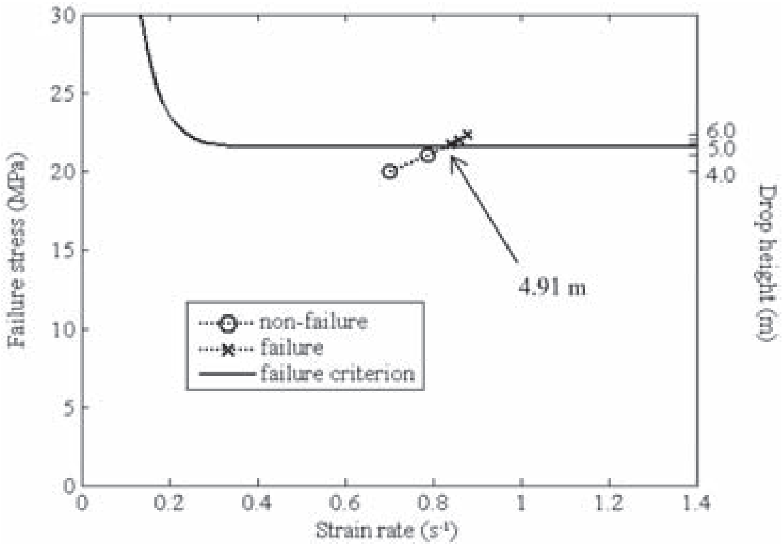

Figure 11 Proposed failure criterion used to determine the failure height of the HDPE bottle.

CONCLUSION

In the drop impact test, the rupture region of the PET bottles occurred at the bottom, while in the HDPE bottles it occurred at the wall edge near the bottom. The rupture region on both bottle types indicated that the water collided with the inside wall of the bottles and the wall exploded. The collision of water with the bottle wall could not be investigated using a video camera, but was explored though FE simulation.

The stress-strain curve at failure of the plastic materials depended on the strain rate. The failure stress decreased when the strain rate increased. The proposed failure criterion effectively predicted the failure drop height of the plastic bottles with errors of less than 9.27% for the PET bottles and 5.59% for the HDPE bottles, compared to the mean failure height of the drop impact test given by the ASTM D2463, 2001. Moreover, the proposed FE techniques could cut the cost of production of expensive prototypes.

LITERATURE CITED

Anghileri, M., L.M.L. Castelletti and M. Tirelli. 2005. Fluid-Structure interaction of water filled tanks during the impact with the ground. **Int. J. of Impact Eng.** 31: 235–254.

ASTM D2463-95. 2001. Standard test method for drop impact resistance of blow molded thermoplastic containers. **Annual Book of ASTM Standards.** Vol. 08. 01. 920 pp.

ASTM D638-99. 2000. Standard test method for tensile properties of plastics. **Annual Book of ASTM Standards.** Vol. 08. 01. 920 pp.

ASTM D882-02. 2002. Standard test method for tensile properties of thin plastic Sheeting. **Annual Book of ASTM Standards.** Vol. 08. 01. 920 pp.

Karac, A. and A. Ivankovic. 2009. Investigating the behaviour of fluid-filled polyethylene containers under base drop impact: A combined experimental/numerical approach. **Int. J. of Impact Eng.** 36(4): 621–631.

Masood, S.H. and V. KeshavaMurthy. 2005. Development of collapsible PET water fountain bottles. **J. of Materials Processing Tech.** 162–163: 83–89.

Reed, P.E., G. Breedveld and B.C. Lim. 2000. Simulation of the drop impact test for moulded thermoplastic containers. **Int. J. of Impact Eng.** 24: 133–153.

Suvanjumrat, C., S. Thusneyapan and T. Puttapitukporn. 2007. A suitable mathematical model of PET for FEA drop-test analysis. **KMITL Sci. J.** 7: 6–17.

Suvanjumrat, C., T. Puttapitukporn and S. Thusneyapan. 2008. Analysis of fluid-structure interaction effects of liquid-filled container under drop testing. **Kasetsart J. (Nat. Sci.)** 42: 165–176.

Thiruppukuzhi, S.V. and C.T. Sun. 2001. Models for the strain-rate-dependent behavior of polymer composites. **Composites Sci. and Tech.** 61: 1–12.

Xinran, X. 2008. Test method on the measurement of true fracture strain of thermoplastics materials. **Polym. Testing.** 27: 284–295.

Yuan, C. and J. Xianlong. 2010. Dynamic response of flexible container during the impact with ground. **Int. J. of Impact Eng.** 37: 999–1007.