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Drop-Test Sturdiness Efficiency of Plastic Bottle Shapes

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Abstract

Under various dropping conditions, the geometrical shapes of plastic bottle effects the bottle sturdiness. The dropping conditions consist of dropping height, bottle-impact orientation and floor material. The bottle that can resist the dropping, or drop testing, will not show any crack or breakage after impacting the floor. This paper introduces finite element analysis (FEA) for simulating the strength of bottle models. The dropping simulation was done on bottles made from polyethylene terepthalate (PET), the popular material for soft-drink containers. The computer simulation used MSC.Dytran for its capability to simulate the dropping with liquid interaction. The stress at the bottle wall was analyzed when the impact orientations of the bottle were at 90^o, 45^o and 0^o with the floor. The basic cross-sections of the bottle shape were circle, ellipse, square and rectangle; they were of the same height and capacity. The FEA comparison of the four shapes, at the same drop height from one meter, indicates that the elliptical cross-section bottle is the best in having the drop-test sturdiness efficiency – by not broken at all three dropping angles.

Keywords: drop test, impact, bottle shape, FEA.

1. Introduction

The Computer-Aided Engineering (CAE) is an advanced method for designing any complex plastic-bottle shapes. An advantage of the CAE is its capability in predicting the strength of the bottles without making physical prototypes. In our previous researches, we used the Finite Element Analysis (FEA) as our CAE tools in making the strength analyses of plastic bottles under the static top load test [1], and static pressure test [2]. According to the drop-test standard [3], the static approximation does not provide a good enough accuracy for simulating the drop test, which is under dynamic condition. With the available dynamic FEA software, the drop test simulations of bottles with water filled were performed [4, 5]. These researches, on the drop test with fluid interaction, provided our initial information for simulating the drop test of the fluid-filled plastic bottles.

This paper used the aforementioned methods for analysis the sturdiness of bottle shapes at various drop test conditions. The topic of our study can provide the basic information for designers and manufacturers for producing their bottles with the sturdiness that will pass the drop test. With this information, it can reduce time and material loss for the redesign of the bottle, and thus, reduce costs and the energy consumptions.

2. Geometrical Shapes of Bottles

Four basic geometrical shapes of bottles are identified by their cross-sectional area, they are circle, ellipse, square and rectangle. The drawings of the four bottles are illustrated in Figure 1.

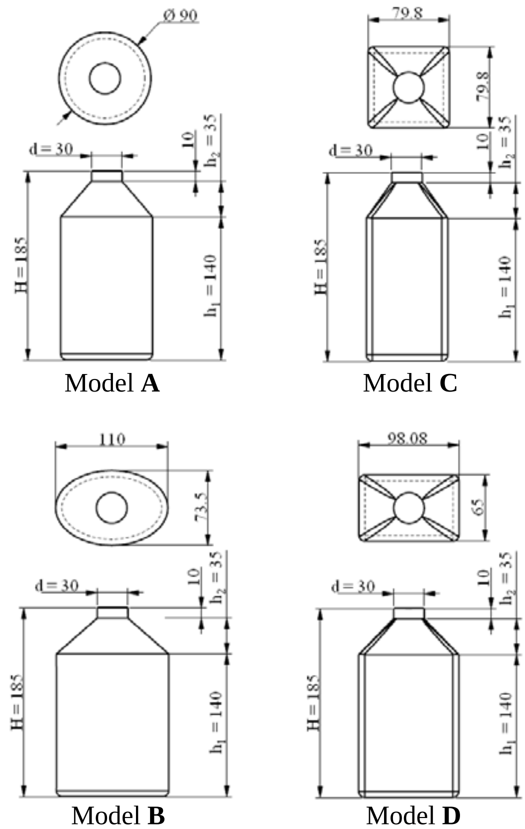


Figure 1. The dimension of the four bottle shapes, unit is mm.

Each model had the same height (185 mm), cap diameter (30 mm), bottleneck height (35 mm) and capacity (1,000 cc ± 5 cc).

The details of the bottles A to D are summarized in Table 1; for cylindrical, elliptical, square and rectangular shapes respectively.

Table 1. The description of the bottle models.

Models	Wall thickness (mm)	Base Area (mm^2)	Height (mm)	Volume (mm^3)	Mass (gm)
A	1.0	6361.73	140	1002.80	70.35
B	1.0	6349.79	140	1001.42	72.16
C	1.0	6368.04	140	999.37	75.34
D	1.0	6375.00	140	1000.47	76.79

3. Finite Element Models

The procedure as described in [4, 5] were applied for creating the Finite Element Model (FEM). Each analytical model for the drop test consisted of the FEM of bottle, rigid floor and fluid domain. The FEM for bottles were represented by shell elements with one millimeter thickness, and they were the combination of quadratic (Quad.) and triangular (Tri.) shapes. Polyethylene terepthalate (PET) was assigned to the material property in the FEA software for the four bottle shapes. The mathematical model of PET was the SRPR stress presented by Suvanjumrat, C., et al. [6, 7]. The FEM information, of the four bottles, is shown in Table 2.

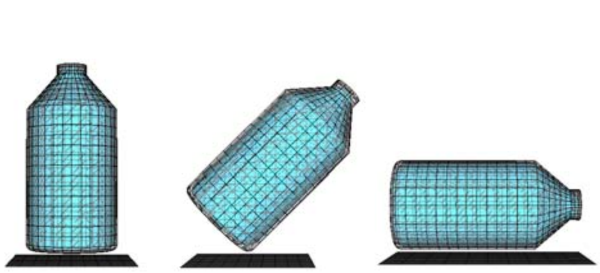
Table 2. The description for the FEM of bottles.

Models	Wall Thicknes s (mm)	Number of Element	Number of Node	Element Type
A	1.0	1,152	1,122	Quad., Tri.
B	1.0	1,152	1,122	Quad., Tri.
C	1.0	1,540	1,506	Quad., Tri.
D	1.0	1,540	1,506	Quad., Tri.

The FEM of the rigid floor was represented by 100 quadratic elements, which made the size to 100 x 100 mm^2.

The liquid used for filling the bottles was water, at room temperature, with the density of 997 kg/m^3. The fluid domain was created by 120,000 hexagonal elements, and used the coupling algorithm [8]. The water was filled in the bottle at full capacity.

The simulations were done at four orientations or at the impact angles of 90^o, 45^o and 0^o. Figure 2 illustrated the three impact orientations of the bottle A.



(A) (B) (C)

Figure 2. Impact angles with the floor: A) 90^o, B) 45^o and C) 0^o.

The drop height for each test was one meter. To avoid the divergence in the computation and to reduce the computational time, during the simulation, we placed the FEM of bottle at 10 mm above the rigid floor, and assign the initial velocity equivalent to that of the required drop height.

The pre-processing and post-processing were performed by using MSC.Patran software version 2005 and the processing was MSC.Dytran version 2005.

4. Results and Discussions

The breaking condition, when using the SRPR stress, is at the strain greater than 1.2 [7]. Table 3 compares the sturdiness of the four bottles by determining the breakage of the bottle at the three impact angles. At the impact angle of 0^o, all four shapes demonstrated no breakage. The impact angle of 45^o resulted in the breakage of three shapes, only the bottle B (elliptical cross-section) survived the drop. At the angle of 90^o, the square and rectangular cross-section bottles fail the drop test. We can conclude from this table that the elliptical shape is the best one from the four investigated shapes, and the cylindrical shape is the second.

Table 3. The drop test simulation result.

Models (Cross-Section)	Impact Angle		
	90^o	45^o	0^o
A (Circle)	pass	**fail**	pass
B (Ellipse)	pass	pass	pass
C (Square)	**fail**	**fail**	pass
D (Rectangle)	**fail**	**fail**	pass

The drop test results from the FEA analysis provided the time variation of the bottle deformation and stress. Figure 3 illustrates the color contour of the stress and the deformed body during the drop test simulation of the cylindrical bottle (model A), with the impact angle of 90^o, at four instant of times: 449.62, 452.06, 454.85 and 457.58 msec. The time at zero second is at the release time.

Notice that the ranges of the stress in the color contour, of each figure, are not equal. The existence of the stress during the free fall or before the bottle impact the floor (at time 0.1 msec) was the result from the fluid interaction. The figure at time of 457.58 msec illustrated the bottle bouncing up above floor.

When the cylindrical bottle engaged the floor at the impact angle of 90^o, the maximum stress was observed to be distributed around the base and the lower wall near the base (Figure 3, at 452.06 msec). After that instant, the stress decreased – and spread through out the whole bottle (Figure 3, at 454.85 msec). Hence the cylindrical wall provides a good stress absorption. The similar result was found with the elliptical bottle.

Dissimilar result was found for the square and rectangular bottles. These two shapes had the stress concentrated locally at the corners of the base, as shown in Figure 4. This small localized and high magnitude of the stress reduced the ability to the quick dispersing of the stress to the larger wall area – hence cause the failure or breakage of the bottle.

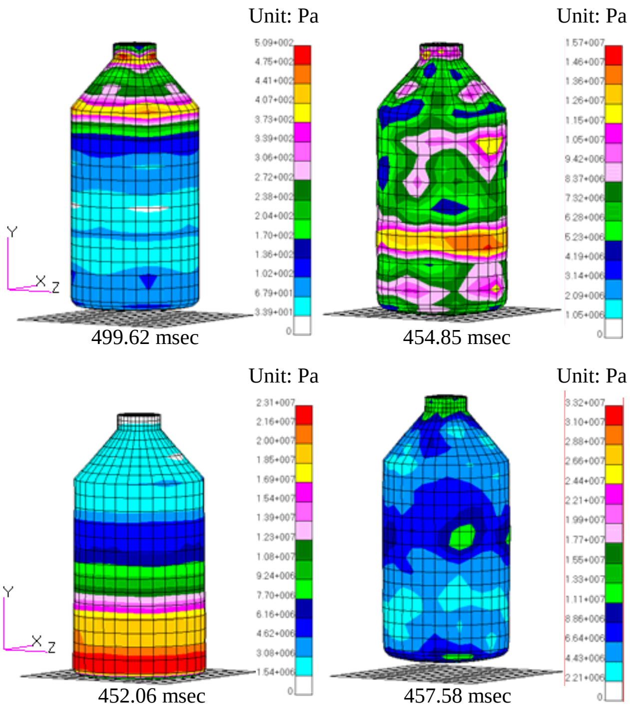


Figure 3. Stress contours, during the dropping, of the cylindrical bottle at four instant of times.

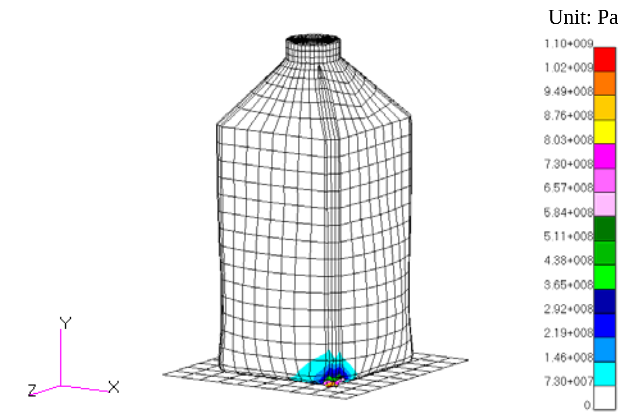


Figure 4. Stress of the square bottle when drop at the 90^{o} angle.

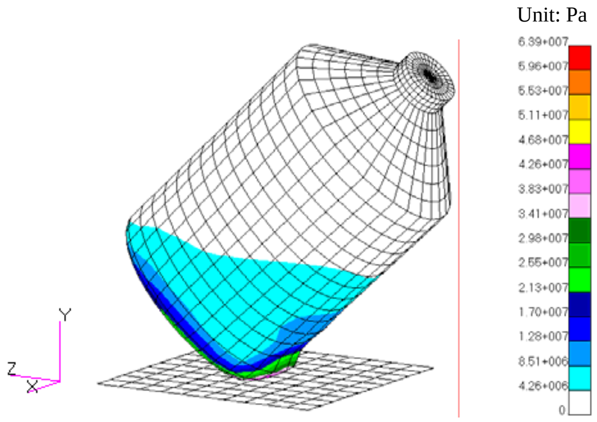


Figure 5. Stress distribution of the elliptical bottle at 45^{o} dropping angle.

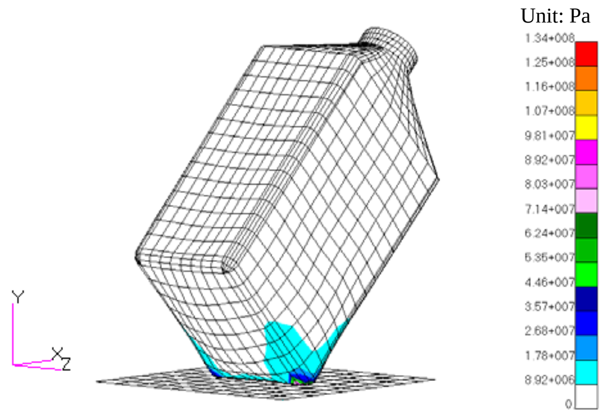


Figure 6. Stress distribution of the rectangular bottle at 45^{o} dropping angle.

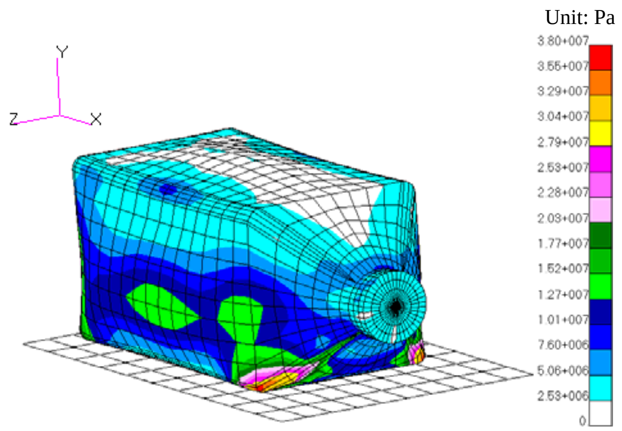


Figure 7. Stress contour of the square bottle at the impact angle of 0^{o}.

The impact angle of 45^{o}, the elliptical bottle was the only shape that was not broken from the one meter drop height. The stress contour of the elliptical bottle is shown in Figure 5. When comparing the stress contour of the elliptical bottle with the rectangular bottle (Figure 6), a larger area of the "stress distribution" is found in the elliptical shape than the rectangular shape. Also, the larger area of "high stress concentration" is found in the rectangular shape than the elliptical shape; for which the rectangular shape has it at the two impact corners.

When the bottles were drop at the impact angle of 0^{o} with the floor, all four shapes indicated no breakage. Examples of the stress contour of the square bottle are shown in Figures 7 and 8. The contour of Figure 8 was 1.36 msec apart from that of Figure 7. In Figure 7, the high stress areas are at the two corner-edges between the bottleneck and the body of the bottle. The second occurrence of high stress area is also found at 1.36 msec later, and at different locations – at the two corners of the base of the bottle (Figure 8).

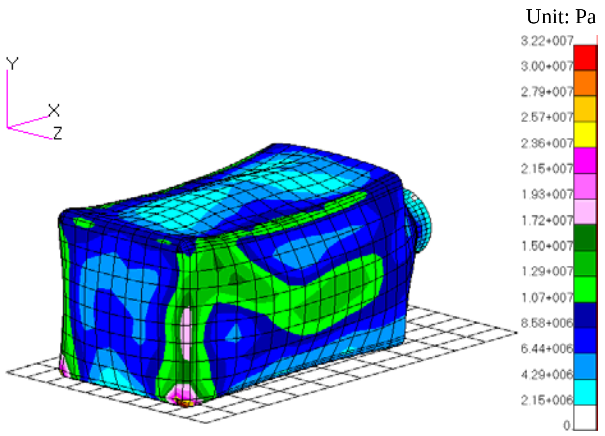


Figure 8. Stress contour of the square bottle at the impact angle of 0^o at 1.36 msec after that of Figure 7.

The stress of each bottle at the impact angle of 0^o was lower than that of the other two orientations. This lower stress comes from the fact that the contact area between the bottle and the floor is relatively large – hence less possibility of failure.

The sloshing of the water inside the square bottle is shown in Figure 9 at the time after dropping from one meter high at 449.28, 452.75, 454.11 and 456.99 msec. The sloshing of the liquid influences the deformation of the bottle as well as the stress.

5. Conclusion

From the FEA simulation of the drop test at the four impact angles, the PET bottle with elliptical cross-section found to be the most sturdiness on not having any breakage – and by having the highest capacity and relatively low mass. The cylindrical bottle has the best volume to mass ratio but found to be the second best basic bottle shape; as it has more tendencies for breaking at the 45^o impact angle than the other two angles. Bottles with sharp corners, such as the square and rectangular shapes, have lower sturdiness-efficiency; they are heavier and slightly less capacity.

The conclusion from our study, for designer, is the bottle shapes with smooth continuous surface and having no edges at the wall is preferred in the resisting of the impact force during the drop test.

That is we must avoid the design of having edges formed by two perpendicular walls, as well as corners from the three perpendicular planes; since they give high stress concentration and reduces the effectiveness in the quick distribution of stress to the larger wall area, during and instant after impact the ground.

Acknowledgment

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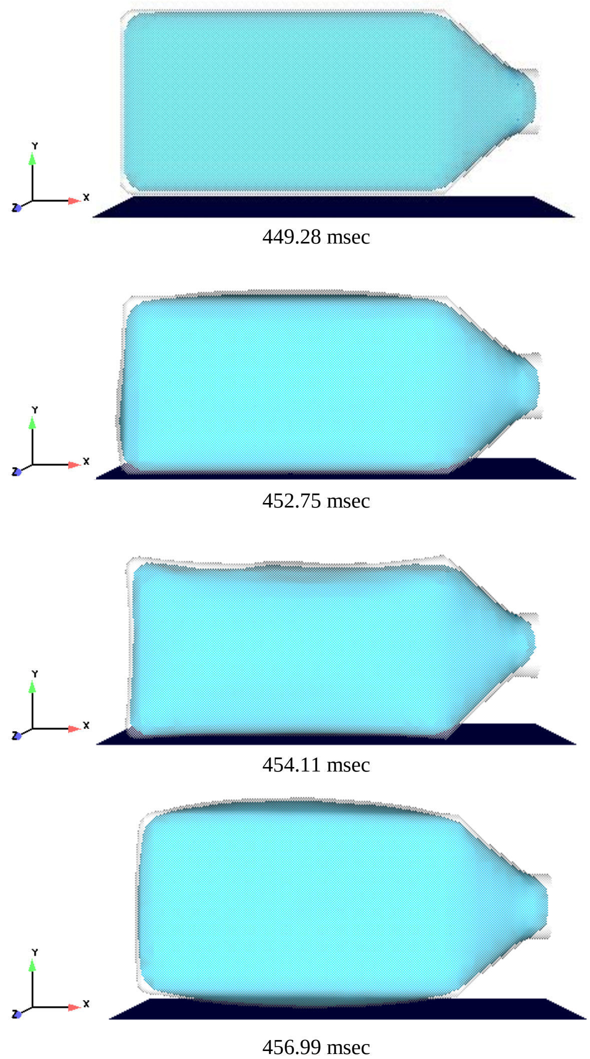

Figure 9. The sloshing inside the square bottle when dropping at the angle of 0^o.

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