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Analysis of Brittle Fracture of Soda Glass Bottles under Hydrostatic Pressure

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Imperfections in glass formed during manufacture or subsequent transportation can weaken bottles, creating a hazard by causing them to fail at lower pressure. When soda glass bottles are pressurized to fracture, the crack density in the broken glass and the fracture pressure are highly correlated. A higher fracture pressure yields a higher crack density as a result of the greater amount of stored energy released on fracture. Thus, after failure it is possible to estimate the pressure to which a bottle was subjected by analyzing the glass fragments. The crack patterns and density agree with analytical models for crack branching in brittle materials under stress. The crack patterns of pressurized bottles subjected to impact are also observed, and a minimum side impact velocity of 2.0 m/s for rupture of pressurized commercial soda glass bottles is determined.

Keywords: brittle fracture, crack branching, crack density

Key Points

- Discontinuities can significantly reduce the fracture pressure of commercial soda glass bottles.
- The density of crack patterns is highly correlated to fracture pressure, allowing for postfracture estimation of prefracture pressure.
- Crack density versus fracture pressure of bottles is in agreement with theoretical models.
- The initial crack is a straight line (as opposed to a star) in agreement with theoretical predictions.
- Minimum impact velocity for rupture of pressurized commercial soda glass bottles is 2.0 m/s for side impacts.

Introduction

Soda glass bottles are often used to store beverages at elevated pressures, which are often due to CO_2 pressure resulting from carbonation. Bottles must not only be properly designed, but also properly manufactured, transported, and stored in order to ensure that they meet safety requirements. Imperfections induced during manufacturing or damage that occurs during subsequent transport and storage can markedly reduce the pressure required to cause fracture of bottles, creating a potential safety hazard. Variations in glass thickness produced during forming, as well as residual stresses produced due to improper annealing, may also lower the failure pressure. If the pressure required to cause fracture of a bottle is not sufficiently higher than its actual pressure, low-pressure impacts that occur during normal handling may cause the bottle to explode catastrophically. On fracture, the release of stored energy results in a violent release of liquid and sharp glass fragments, posing a safety hazard.

This paper analyzes the crack patterns of commercial soda glass bottles hydraulically pressurized to failure. It is found that the density of cracks in broken bottles is highly correlated with the fracture pressure, with a higher fracture pressure resulting in a higher crack density. This is due to the increase in stored energy with increasing pressure. The additional surface area created by fractures requires energy, and the increasing amount of stored energy with increasing pressure allows for a higher density of cracks.

The density of cracks as a function of fracture pressure is found to increase, which is in agreement with theoretical models of crack branching. Furthermore, the crack initiates along a line, as opposed to a star with multiple branches. This single line of fracture at the origin is in agreement with theoretical predictions.[1]

Also examined is the fracture behavior of commercial beverage bottles on impact with a hard object.

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The bottles were still full and under pressure. No clear trend is observed with regard to fracture behavior, but a minimum side-impact velocity of 2.0 m/s for the rupture of pressurized bottles is determined. Due to the stored energy in the pressurized, carbonated beverage, the rupture of the bottles is very violent.

Experimental Procedure

Fracture Due to Hydraulic Pressure

Commercial brown soda glass bottles were filled with water and pressurized hydrostatically to fracture. A clamp providing a tight seal between the pressure source and the bottle was constructed. The seal was provided by a rubber washer machined to fit snugly against the inside and outside of the bottle neck. Epoxy was used to improve the seal and attach the washer to the bottle. A hose clamp on the outside of the bottle provided further support. Hydraulic pressure was applied through a tube inserted in the center of the washer, which was also sealed with epoxy.

Each bottle was filled completely with water prior to application of hydraulic pressure. Because water is nearly incompressible, the total amount of stored energy at failure is much less than it would be if the bottles were pressurized with carbon dioxide. The rupture of the bottle is therefore much less violent, reducing the likelihood of additional fractures in the glass due to secondary collisions. (The amount of energy stored in the strained soda glass is the same, irrespective of whether the pressurizing medium is air or water.) Prior to pressurization, the bottles were loosely wrapped in soft paper to minimize fractures from secondary collisions and placed in a secondary containment vessel.

Scratches were introduced in the side of some of the bottles, approximately one inch from the base of the bottle. The scratches were introduced with a diamond scribe and oriented either horizontally, vertically, or at a 45° angle relative to the base of the bottle. In the bottle that failed at 0.14 MPa (20 psi), a groove was ground into the side of the bottle with a grinding wheel. The purpose of the scratches was to introduce stress concentrations to cause fracture at lower pressures. After pressurization to fracture, each bottle was reassembled using transparent tape and photographed to reveal the crack pattern.

Fracture Due to Impact

Commercial beverage bottles in the as-purchased state (unopened and still full of liquid) were oriented horizontally and dropped from different heights so that the impact would be to the side of the bottle. Bottles were dropped onto a flat surface, onto a sharp 90° steel corner, and onto a rounded steel cylinder of approximately 5 cm diameter. The angled corner and cylinder were secured and of sufficient mass so as to not be moved by the impact. In order to obtain higher velocities, bottles were also held by the neck and swung downward into the objects. A high-speed video camera was used to film the impacts at a rate of 1000 frames/s. A backdrop displaying heights allowed the impact velocity to be measured directly by comparing the positions of the bottle in consecutive video frames.

Results and Discussion

Fracture Due to Hydraulic Pressure

On examination of the bottles fractured by hydraulic pressure, several important results were found.

First, not all of the bottles with induced discontinuities broke at the induced discontinuities. However, for all bottles that did not fail at artificially-induced discontinuities (including bottles with no induced discontinuities), fracture initiated at the base of the bottle. Figure 1 shows one such bottle, which broke at 2.25 MPa. This is most likely due to the stress concentration present where the side of the bottle joins the base. Figure 2 shows a finite-element simulation of the stress concentrations present in a representative soda glass bottle pressurized to 1.39 MPa (200 psi). The simulation was performed using Pro/ENGINEER (Parametric Technology Corp., Waltham, Mass.), and the bottle dimensions were taken from a representative bottle from actual experiments. The bottle diameter was measured to be 6.48 cm, and the mean wall and base thicknesses were 0.178 and 0.432 cm, respectively. It is noted that glass thicknesses may vary as much as 50% within bottles. An adaptive mesh technique was used, and subsequent solving and post-processing were all handled within the Pro/MECHANICA (Parametric Technology Corp., Waltham, Mass.) software environment. As seen in Fig. 2, the maximum stress occurs at the base of the bottle, with the maximum calculated stress being

2.4×10^7 Pa. This is one-fourth of the yield stress, which is approximately 1×10^8 Pa.[2] Figure 3 shows the stress concentrations with a discontinuity induced in the bottle. The discontinuity introduces stress concentrations, which make it a prime location for crack initiation.

Second, for those bottles in which cracks initiated at induced flaws, the initial crack was oriented along the bottle axis, or perpendicular to the stress gradient. The orientation of the initial crack was independent of the orientation of the induced defect. This is in agreement with Ref 3, where it is reported that flaw size is the critical factor in determining failure stress and that flaw shape and location are of much less importance. For all bottles tested, crack branching tended to orient the cracks along the bottle axis. This is reasonable, because crack propagation perpendicular to the stress would release the most energy. Similar findings have been reported for the fracture of rectangular bars tested in flexure, where crack branching led to cracks perpendicular to the induced stress.[4]

Third, it was observed that in all cases where fracture was initiated at an induced imperfection, the initial crack was a line, as opposed to a star with many cracks extending from a single nucleation point. Griffith theory has been used to analyze crack nucleation in a homogeneous plate under axisymmetric tension to determine the equilibrium number of cracks extending from the crack nucleation point.[1] Increasing the number of cracks lowers the strain energy of the system. However, energy is required to create the additional surface area of the crack faces. The equilibrium number of cracks is the one that minimizes the total energy of the system, which is the strain energy plus the additional surface energy due to crack formation. The equilibrium number of cracks extending from a crack nucleation point is always two, resulting in a straight line.

The model also predicts the crack lengths of subsequent cracks after branching. The key result is that all crack length segments vary inversely with the square of the applied stress. This implies that as the

Fig. 1 *Broken bottle with crack initiation at the base of the bottle. Test pressure was 2.25 MPa.*

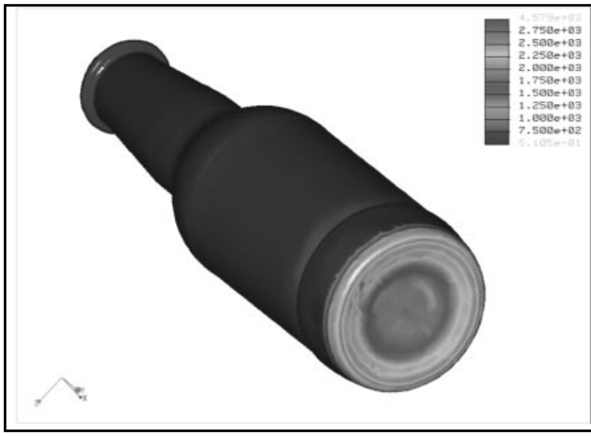

Fig. 2 *Finite-element simulation of stress concentrations in pressurized soda glass bottle. The maximum stress is 2.4 $\times 10^7$ Pa and is located at the edge of the base of the bottle.*

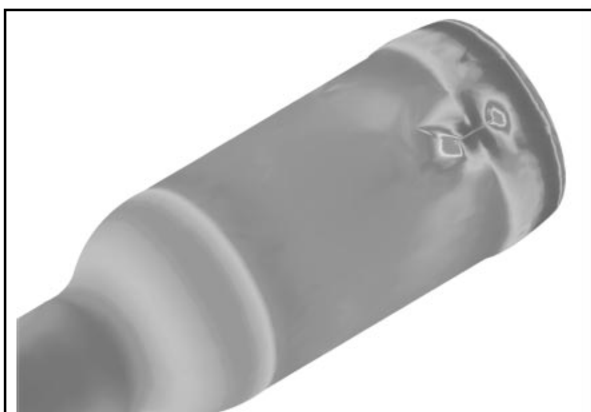

Fig. 3 *Finite-element analysis of stress concentrations in a pressurized soda glass bottle with a discontinuity*

test pressure increases, much more crack branching in the glass should be observed.

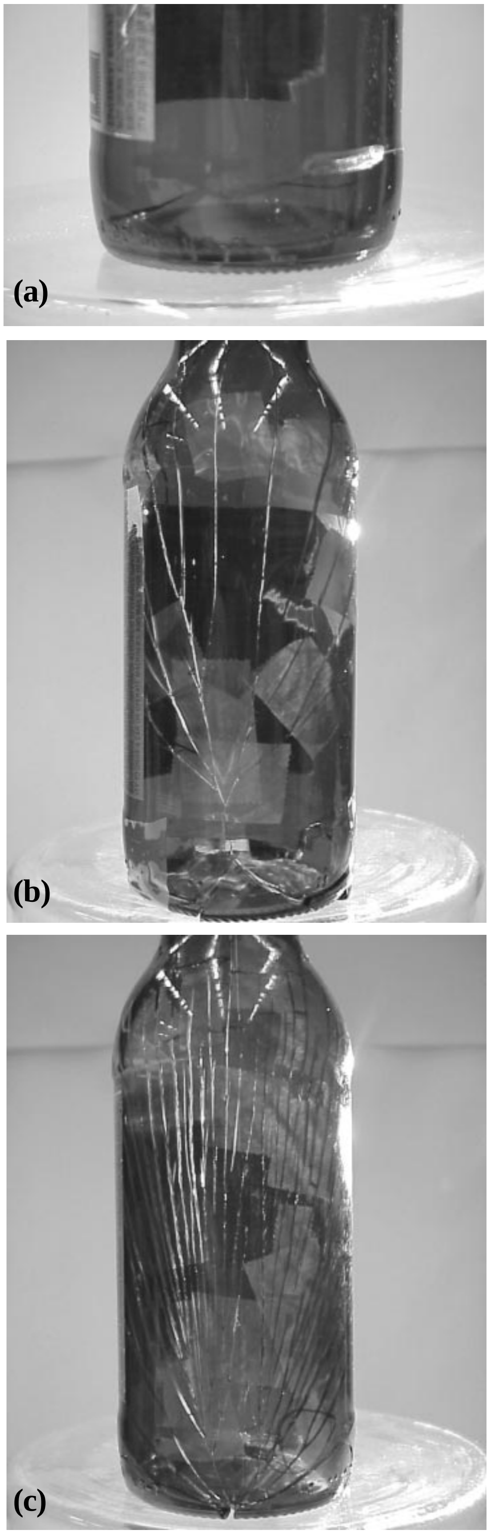

Fig. 4 *Fractured bottles with failure pressures of (a) 0.14 MPa (20 psi), (b) 1.32 MPa (190 psi), and (c) 2.71 MPa (390 psi)*

Figure 4 shows bottles with the test pressures of 0.14, 1.32, and 2.71 MPa (20, 190, and 390 psi, respectively). The increase in crack density is evident from these samples and was consistently observed in all samples tested.

In order to quantify the crack density, the number of cracks crossing a semicircle of 3.8 cm (1.5 in.) radius, at the center of which was the point of crack initiation, were counted. The semicircle was oriented upward (away from base of bottle) to count cracks on the walls of the bottle and not on the bottom surface of the bottle. The crack patterns in the base of the bottle were much different and showed no clear trend. This may be due either to the much thicker glass or the different stress concentrations in the base. However, as shown in Fig. 4, the crack patterns on the sides of the bottle were well behaved and regular. Figure 5 shows the number of cracks crossing the semicircle of 3.8 cm (1.5 in.) radius as a function of fracture pressure. The data has very little scatter and clearly rises parabolically as a function of pressure, in agreement with theoretical predictions.

The fact that crack density increases in a regular and predicable fashion with increasing test pressure allows a method for determining failure pressure from bottles after they are ruptured. By analyzing the size of the broken pieces, or the crack density, the pressure prior to the fracture event can be estimated, and it can be determined whether or not

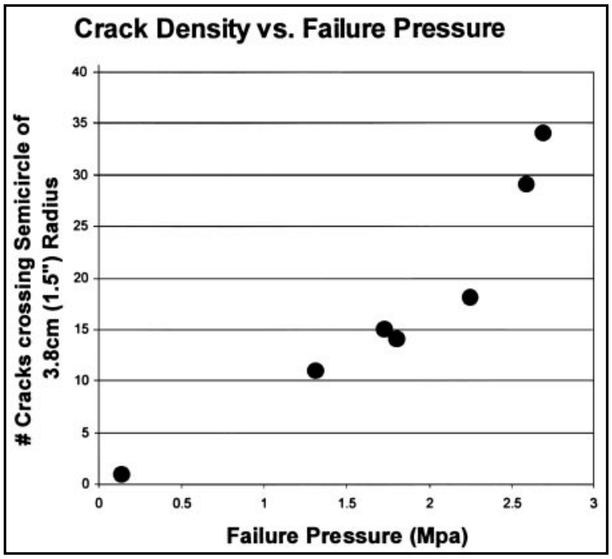

Fig. 5 *Number of cracks crossing a semicircle of 3.8 cm (1.5 in.) radius as a function of test pressure*

the bottle contained a strength-limiting imperfection, regardless of whether the origin was recovered or not. It is noted that this method is valid for bottles breaking from pressure and not from impact.

The explosions in these tests were purely hydraulic, whereas crack events in bottles sold as consumer products are both hydraulic and pneumatic, due to the compressed gas present in the bottle. However, the initial crack branching in the region near the origination point is the same for either case. The reason for this is that the crack propagation velocity is near the speed of sound in glass, which is 5.1×10^3 m/s.[5] This is more than three times the speed of sound in water, approximately 1480 m/s,[5] which is the maximum speed at which pressurized gas can transfer additional energy through the liquid. The area of crack initiation in this study is near the base of the bottle, several inches away from the water/air interface, so the region of crack branching studied is purely hydraulic in nature during the time scale of the brittle fracture, regardless of whether or not the top of the bottle contains pressurized gas.

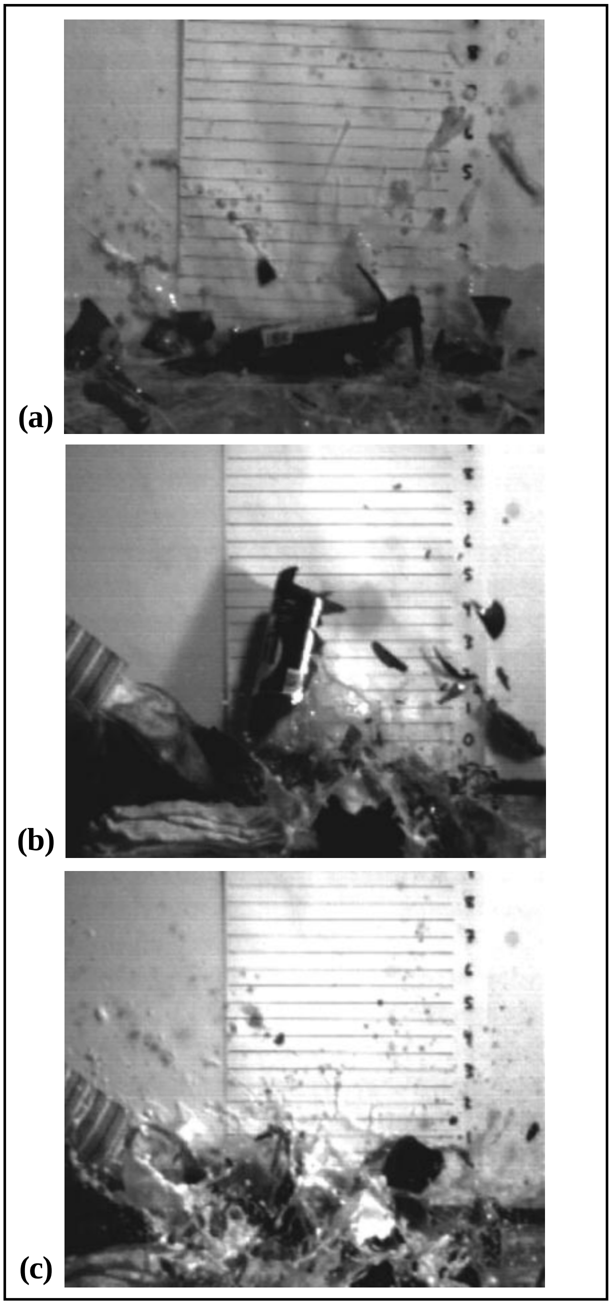

Fig. 6 *(a) Bottle impacting a flat surface at 279 cm/s. (b) Bottle impacting 90° corner at 330 cm/s. (c) Bottle impacting 90° corner at 838 cm/s*

Fracture Due to Impact

For fracture due to impact, no clear trend was observed with regard to fracture behavior. Bottles were oriented horizontally and dropped onto the flat, angled, and rounded surfaces from heights ranging from 10 to 40 cm. A minimum impact velocity of 2.0 m/s was observed for the rupture of pressurized bottles corresponding to a drop from 20 cm. Above this height, some bottles burst and some did not, although bottles that survived drops from as high as 35 cm were observed.

At least two reasons exist for the variation in the impact velocity necessary for bottle rupture. First, as previously noted, there was significant thickness variation in the glass both between and within bottles. This results in variations in the impact velocity necessary for failure. Second, it was experimentally difficult to produce impacts on the same location on the bottle and with the same bottle orientation. The location and angle of the impact are important in determining whether or not the bottle ruptures.

It was observed that fractures due to impact were very violent due to the release of stored energy in the pressurized liquid. Figure 6 shows three bottles immediately after rupture. The foaming of the carbonated liquid, due to the nucleation of carbon dioxide bubbles, expands the liquid and throws pieces of glass into the air, creating a potentially hazardous situation for nearby persons.

Conclusions

Commercial soda glass bottles were pressurized to fracture and the resulting crack patterns were investigated as a function of pressure. Crack density increases parabolically with increasing test pressure, which is in agreement with theoretical models. For those bottles in which cracks initiated at artificially-induced stress concentrations, the initial crack is found to always be a line oriented perpendicular to the stress gradient, independent of the orientation of the induced discontinuity. Bottles in which cracks did not initiate at induced discontinuities always failed where the base of the bottle meets the sidewall, which is the location of the maximum stress concentration. For fractures of pressurized bottles due to impact, a minimum necessary impact velocity of 2.0 m/s was observed in the test conditions described previously. The stored energy in the liquid resulted in violent ruptures, creating a potentially hazardous situation for nearby persons.

Acknowledgment

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