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Investigating the behaviour of fluid-filled polyethylene containers under base drop impact: a combined experimental/numerical approach

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Abstract

In this work, the behaviour of fluid-filled plastic containers under base drop impact is investigated using a combined experimental/numerical approach. In addition, theoretical predictions from two approaches, waterhammer theory and a mass-spring model, are also given. Experimental tests are conducted using a specially designed rig for testing plastic containers (bottles). Tested containers are fully instrumented with pressure transducers and strain gauges. The experiments are simulated using a two-system fluid-structure interaction procedure based on the Finite Volume Method. Good agreement is found between measured and predicted pressure and strain histories. Results obtained are in favour of waterhammer theory.

Keywords

base impact, polyethylene containers, waterhammer, mass-spring model, fluid-structure interaction, Finite Volume Method

1. Introduction

The most commonly used drop impact test procedure is one defined by ASTM and ISO standards [1,2,3]. Here, a measure of the drop impact resistance of blow-moulded containers is provided as a summation of the effects of material and manufacturing conditions, container design, and other factors. The result of a test is failure or non-failure. Hence, any additional information about the behaviour of fluid-filled containers under drop impact such as pressure in a fluid when failure occurred, strain in the bottle wall, effects of strain or pressure rate, etc. are not available. However, the failure of fluid-filled containers under drop impact does depend on a number of parameters such as drop impact mode, the material properties of both the container and its liquid contents, container geometry and design, and so on. If any parameter is changed, a new set of tests has to be conducted. It is clear that this approach can be very expensive, especially in design optimisation. This undoubtedly emphasises the importance of instrumented testing, and corresponding numerical simulation.

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There has been a limited amount of work conducted in this area. For example, Reed *et. al.* [4,5] conducted drop experiments on both poly-vinyl-chloride (PVC) and polyethylene (PE) bottles. They recorded pressure histories at different positions in the bottle and observed that the pulse time was independent of the drop height. Reed's work was continued by Lim [6], who conducted extensive instrumented drop impact testing on blow-moulded 600 cm^3 detergent bottles and 210-litre drums. The containers were filled with water at different levels and dropped squarely from varying heights onto a specially constructed plate to record the total impact force on the floor. In order to record pressure transients, two pressure transducers were mounted inside the containers at various positions. He found that the magnitude of the pressure pulse always increases linearly with the impact velocity, but decreases parabolically with distance from the base and interpreted his results using waterhammer theory. Later, Breedveld [7] studied the wave speed along 20-litre drums subjected to drop impact. He observed that there was no time delay between pressure signals at two different positions from the base. In other words, he claimed there was no wave travelling through the water contained in the container. This observation has been used to establish the mass-spring model for drop impact of fluid-filled containers.

It is clear by now that there is still no convenient method to explain this complex problem. This paper will try to shed some more light on the problem and give new approaches to solving it.

2. Container types and materials

The present investigation is focused on small containers and simple container designs, ie. a small 1-litre bottle with a circular cross section. Experimental results are obtained for the simplest drop impact case, ie. the base drop with and without originally manufactured base, and used in subsequent analysis and comparison with numerical simulations. A schematic of such a container, supplied by BP Chemicals, is given in Fig. 1 along with main characteristics and dimensions. The containers are made of high-molecular weight copolymer grade Rigidex with material properties given in Fig. 1.b, where the properties of the liquid used are also given.

Fig.1 A 1-litre bottle used to investigate drop impact of plastic containers – a) geometry b) geometrical and material data

3. Methods of analysis

3.1 Theoretical predictions

There are two main approaches used to theoretically predict the behaviour of plastic containers under base drop impact: waterhammer theory [8-10] and the mass-spring model [7]. According to the classical theory, waterhammer is a term used to describe unsteady flow in fluid-filled pipe systems caused by a sudden change in the flow velocity. On the other hand, mass-spring model theory considers the fluid-filled container as a mass-spring system. Therefore, there is a basic difference between these two approaches: waterhammer theory states that there is a pressure wave formed at the container base due to impact, which travels through the bottle-water system, whereas the mass-spring model theory assumes that there is no wave travelling and the entire water-filled container behaves as a lumped dynamic system. Details of the analysis using both methods can be found in [11] and only the basics are given here.

Wave speed

The wave speed (the speed of sound) in the unconfined liquid, c_{un}, in a medium, is given by:

$$c_{un} = \sqrt{\frac{K}{\rho}} \tag{1}$$

where K is the bulk modulus, and ρ is the density of the contained liquid. The same equation can be applied to a rigid pipe system, since all fluid kinetic energy is converted only into strain energy due to compression of the liquid (Lewitt [12]). However, in an elastic pipe system, where the effect of pipe elasticity has to be taken into account, the fluid mass entering the pipe also fills the extra volume due to an increase in the pipe cross-section area. It can be shown (e.g. Wylie and Streeter [9]) that the pressure wave speed in such cases is given by:

$$c = \sqrt{\frac{K}{\rho \cdot (1 + \frac{D}{t}\frac{K}{E})}} = \frac{c_{un}}{\sqrt{1 + \frac{D}{t}\frac{K}{E}}} \tag{2}$$

where D is the pipe diameter, t the pipe wall thickness, and E the Young's modulus of the pipe material.

Period and pressure magnitude

Waterhammer is a cyclic event with period [8]:

$$T_{WH} = \frac{4L}{c} \tag{3}$$

where L is the length of the pipe.

The pressure magnitude can be obtained in various ways, resulting in the Joukowsky equation [13]:

$$\Delta p_{WH} = \pm \rho \cdot c \cdot \Delta v \tag{4}$$

where Δv is a change in velocity caused by sudden valve closure. Eq.4 shows that pressure rise does not depend on the pipe length, and is directly proportional to the wave speed through a system.

On the other hand, the period and pressure magnitude for mass-spring model theory can be obtained using a simple energy principle, and basic mathematics. In their analysis, Reed *et. al.* [7] assumed a linear pressure distribution along the bottle axis (rather than a parabolic one, observed in experiments), since it is in agreement with simple Newtonian mechanics: assuming the container to be short enough so that all sections of the container have the same deceleration, the upward force at any water level from the base is proportional to the mass of water above it. As a result, the following expressions can be obtained:

$$p_{max} = \sqrt{3} v_0 \sqrt{\frac{K\rho}{1 + \frac{K}{E}\frac{D}{t}}} = \sqrt{3}\Delta p_{WH} \tag{5}$$

$$T_{MS} = \frac{2\pi L}{\sqrt{3}c} \approx 0.91 \cdot T_{WH} \tag{6}$$

From the above expressions it can be concluded that the maximum pressure is at the base and its value is $\sqrt{3}$ times higher than that predicted by waterhammer theory; the pressure decreases linearly along the container axis. The period of system oscillation, however, is 9% shorter than that obtained by waterhammer theory.

Natural oscillation

A sudden pressure pulse applied to a pipe/bottle wall excites the system to oscillate with so-called `barrel' mode or natural oscillation. For a very long system such as a pipe, the period of the `barrel' mode oscillation is much shorter than the waterhammer period and its influence on a wave travelling through the system is not significant. However, its value can be of the same order of magnitude for a short system, such as a fluid-filled container, and natural oscillation then has to be taken into account in the analysis.

It can be shown that the period of natural oscillation for a cylindrical water-filled system subjected to an internal pressure is (Reed [7], Protopapas[14]):

$$T_{NO} = 2\pi\sqrt{\frac{KR^3(2t\rho_{pipe} + R\rho_{wat})}{2KREt + (Et)^2}} \approx 2\pi\sqrt{\frac{\rho_{eff}D^2}{4\mathrm{E}}} \qquad (7)$$

where ρ_{eff} ($=\rho_{pipe}+D\rho_{wat}/4t$) is the effective density of such a system and that of an empty cylindrical container is:

$$T_{NOe} = 2\pi\sqrt{\frac{\rho_{pipe}D^2}{4E}} \qquad (8)$$

Stress and strain predictions

The maximum hoop stress can be obtained using the thin-wall assumption, ie.

$$\sigma_\theta = \frac{p_{max}D}{2t} \qquad (9)$$

and the strain in the container wall is:

$$\varepsilon_\theta = \frac{p_{max}D}{2tE} \qquad (10)$$

where maximum pressure p_{max} is given by equations 4 and 5 for waterhammer and mass-spring model theories, respectively. Predictions for the drop height of 0.5 m (impact speed of 3.13 m/s) are summarised in Table 1.

Table 1 Predictions for drop height of 0.5 m

Wave speed c_{un} (Eq.1), m/s	1485	T_{NOe} (Eq.8), ms	0.23
Wave speed c (Eq.2), m/s	151.7	Maximum pressure, WH, (Eq.4), bar	4.77
T_{WH} (Eq.3), ms	3.28	Maximum pressure, MS, (Eq.5), bar	8.2
T_{MS} (Eq.6), ms	2.98	Hoop strain for WH (Eq.10)	0.0103
T_{NO} (Eq.7), ms	0.89	Hoop stress for WH (Eq.9), MPa	13.3

3.2 Experimental procedure

In order to thoroughly investigate the drop impact of fluid-filled containers and obtain valuable information for verification of numerical procedures, a special rig for drop impact tests was developed. The experimental set-up is shown in Fig.2. It consists of the instrumented rig, strain gauge (SG) and charge (pressure transducer, PT) amplifiers, and an oscilloscope connected to a computer (4).

Fig. 2 Experimental set-up for instrumented drop impact test

The main part of the set-up is the rig, shown in Fig.3. It is an assembly of two aluminium end-caps held together by three steel tie bars. The rig is positioned in the initial position at a desired height H using a string attached to the hook on the upper cap at one end, and to a quick-release mechanism on the other. The instrumented rig is dropped onto a concrete surface by activating the quick-release mechanism. To ensure square landing of the rig a set of three U-profile guides is used. In addition, a velocity sensor is attached at the lower part of the guides to check the impact speed.

Fig.3 Experimental rig: left – bottle without base; right – bottle with originally manufactured base

The rig is designed to house two types of specimens: those without a base and those with their originally manufactured base. Both specimens are of the same size and type, the first having the base cut from an original. There are two main reasons for this approach. Firstly, the influence of the base shape (rigid and flat as opposed to flexible and complex) on the pressure distribution and strains in the bottle wall can be examined. Secondly, numerical simulation of a drop impact of the bottle with a flat and rigid base is more easily performed and verified than that of the real bottle, for which contact of the base end with the impact surface has to be taken into account.

The specimen without a base is fixed to the lower cap using a Jubilee clip. The caps are made of aluminium to avoid corrosion due to contact with water contained in a test specimen. To avoid leakage, an O-ring is used on the internal specimen surface. The part of the lower cap that is inserted into the bottle has the same diameter as the internal bottle diameter, making the base flat and rigid, as desired. The bottom part of the cap has an annular gap to provide room for the wires connected to the pressure transducers and to keep them away from the impact surface. The cap is instrumented with two Kistler 601A piezoelectric pressure transducers, one being placed in the middle of the base (PT1), and the other 10 mm from the bottle wall (PT2). The signals from the pressure transducers are amplified by the Kistler 568 charge amplifier, and transferred to the Nicolet 500 oscilloscope. When a real bottle is used, it is placed onto the lower cap. In this case, the pressure is recorded by a pressure transducer placed in the length-adjustable PT holder (PT3), which is fixed to the upper cap.

The specimens are instrumented with two RS 632-124 strain gauges to record the deformation of the bottle wall. The signals from the strain gauges are amplified by a Fylde strain gauge amplifier, and transferred to the oscilloscope. The first strain gauge (SG2) is placed 25 mm and the second (SG1) 80 mm from the base (or 50 mm in the case of a real bottle).

Specimens are filled with water to a level of 125 mm from the base. The rig was dropped from four different drop heights (30, 40, 50, and 60 cm). Three independent test series were conducted for each height. All signals were recorded and stored on the computer using a recording frequency of 1 MHz. Voltage signals were later multiplied by appropriate calibration factors to obtain data expressed in pressure units (bar). All tests were conducted from heights much lower than that causing permanent deformation or failure.

3.3 Numerical procedure

To simulate these experiments, a two-system fluid-structure interaction procedure is used. The procedure is implemented in Finite Volume (FV) based software OpenFOAM [15]. As a two-system method, it employs separate solid and fluid domains, both domains being calculated using the FV method in a single unified approach. The basics of the procedure are explained in detail by Greenshields *et. al.* [16], Karac *et. al.* [17-19] and Karac [11].

The bottle and its liquid contents are modelled according to the geometry, material properties and experimental set-up discussed earlier. Only the part of the bottle filled with water is modelled for simplicity, *ie.* the bottle and its liquid content are simulated using a water-filled pipe-like geometry. Assuming a constant wall thickness of the bottle, the problem can be considered as axi-symmetric, and therefore only a section, ie. a slice, of the fluid and solid domains are modelled, as shown in Fig.4. Fluid and solid domains are divided into 50 cells in the z-direction (along the central axis). The solid domain has three cells through the wall thickness (y-direction), whereas the fluid domain is discretised into 20 cells in the same direction. Only one cell is used in x-direction, which makes the problem two-dimensional. Hence, the total number of cells in the solid and fluid parts is 150 and 1000, respectively.

Fig.4 Numerical domain for the case with rigid and flat base

At the instant of impact, both domains have an initial speed V, which corresponds to a drop height H, and the bottom surface for both domains is fixed. Thus a Dirichlet boundary condition ($\mathbf{D}$ =0) is applied to the solid bottom surface, and a wall boundary condition to the fluid bottom boundary ($\mathbf{V}$=0, $\partial p/\partial z$=0). The solid top surface is assumed to be a symmetry plane boundary, the outside boundary is traction free, and the inside boundary has a fixed gradient boundary condition with applied pressure from the fluid domain. The pressure at the fluid top surface is kept constant, simulating a free surface (*ie.* no special free-surface tracking model is implemented in the code) with $\partial \mathbf{V}/\partial z$=0. A symmetry boundary condition is applied to the `plane' representing the central axis, and a so-called *wedge* boundary type (in principle, a symmetry boundary condition), is applied to the axi-symmetry planes. The time step in the simulations was 0.5 μs, the maximum Courant number being approximately 0.00056. Calculation in each time step was stopped and next time step started when convergence for both domains individually and as a system was achieved.

4. Results and discussion

The following discussion is focused on the results from a drop height of 0.5 m, corresponding to the impact speed of 3.13 m/s, unless otherwise stated.

4.1 Experimental results

Results for bottles with a flat and rigid base

Pressure histories from all sensors used are shown in Fig.5-left. It is clear that there is a general similarity in the pattern of all traces. A typical signal from the pressure transducer positioned in the middle of the lower cap (PT1) at a 1 MHz recording rate is shown in Fig.5-right. The signal is distorted by high frequency oscillations of high amplitude, and therefore it is very difficult to accurately analyse the trace. The FFT analysis did not clearly show their origin, but subsequent analyses of tests with empty specimens (no liquid contents) and numerical simulations showed that they are governed by, at least, two separate processes:

- Structural vibrations of the rig, since the pressure transducers are mounted in the aluminium base (lower cap or transducer holder).
- Presence of unconfined waves. At the instant of impact, water away from the wall does not have any information about the wall deformation and waves travel at the unconfined speed of 1500m/s, producing high frequency radial and axial reflections.

A clearer picture can be obtained if the trace is smoothed. The red line in Fig.5-right represents the history smoothed (by averaging over 100 points), thus cancelling out all signals with a period smaller than 0.1 ms. According to this smoothed trace, immediately after impact pressure rises to approximately 5 bar and then suddenly drops to 2.5 bar. This is due to natural oscillations of the bottle wall, which expands radially due to the internal pressure that starts to build up at the base. This increase in diameter then causes a pressure drop next to the bottle wall. Consequently, information about wall movement travels from the bottle wall towards the central axis in a form of pressure drop. The bottle wall continues to oscillate (`breathe') and causes a disturbance of the fluid pressure to travel in the radial direction.

Fig.5 Pressure histories for bottle with flat and rigid base: left – all sensors, right – pressure transducer PT1

The radial `breathing' due to natural oscillation is relatively quickly damped. Pressure continues to drop until the vapour pressure is reached (~0.1 bar absolute pressure). At this stage, even a very small amount of gas (air) present in the water causes the pressure wave to travel at a speed lower than the one expected in a flexible system. This can be easily observed as a longer period of the low pressure part of the trace (from 2 to 5.5 ms). After this event, a new period starts, the pressure rises again, but this time the magnitude of the high frequency oscillations is significantly reduced. The whole event dies out after 15 ms.

Figure 6 presents the pressure histories from two strain gauges: SG1 positioned at 80 mm from the base and SG2 at 25 mm from the base. The SG2 history shows that the impact is followed by a sudden pressure (strain) rise, reaching its maximum of 4.8 bar. The slope of the trace represents the pressure rise rate. The strain rate can be obtained using thin-wall assumption (derivative of Eq.10). Here, the value of 12500 bar/s is obtained, which corresponds to strain rate of 14 s^{-1}. The positive pressure part of the trace (first 1.65 ms), which corresponds to a half of the waterhammer period, is superimposed with small higher frequency oscillations with a period approximately equal to 0.9 ms. Similarly to PT history, these oscillations are attributed to natural oscillations (see Tab.1, T_{NO}, Eq.7). The duration of this part corresponds to the time in which the pressure wave travels two water levels. According to values measured, the wave speed in the system is 155 m/s, and corresponds well to the theoretical value given in Table 1 (Eq.2). Figure 6 also indicates that there is a time delay between the signals recorded by the two strain gauges, thus proving the existence of a wave travelling through the bottle. The time delay at a pressure of 2 bar is around 0.35 ms, which corresponds well to a wave speed of 155 m/s predicted by waterhammer theory.

Fig.6 Pressure histories from the strain gauges

Figure 7-left presents the pressure histories from the strain gauge SG2 for four different drop heights. All traces follow the same pattern, having almost the same period. This is expected according to both waterhammer and mass-spring model theories, since in both cases the period of the main oscillation does not depend on the drop height. On the other hand, the maximum pressure magnitude increases with drop height, and it agrees well with waterhammer predictions as shown in Fig.7-right.

Fig.7 Strain gauge data from different drop heights: left – pressure histories, right – maximum pressure vs. drop height

Results for bottles with an originally manufactured base

Figure 8-left shows pressure histories from all sensors when the bottle with an originally manufactured base is tested. Again, the pattern of all traces is very similar to each other, but noticeably different than that observed in the tests on bottles with a flat base. The pressure rise after the impact is not as fast as in the previous tests, and a long low pressure part of the trace (pressure magnitude around minus 1 bar of relative pressure) has practically disappeared. In addition, many oscillations with significantly reduced magnitude follow the first pressure rise. There are at least two main reasons for such behaviour. Firstly, the original base deforms and

the water is brought to rest over a longer time. Consequently, the pressure rise rate is reduced (valve-closure-time effect). Secondly, the bottle is not fixed at the base, ie. it can bounce after the impact, so the negative pressure period cannot last too long.

Fig.8 Pressure histories for real bottle: left – all sensors, right – strain gauges

As noted for the specimens connected to a rigid base, signal from the pressure transducer is distorted by high frequency oscillations, and so further analysis will be focused on the strain gauge histories. Figure 8-right shows the pressure histories from two strain gauges, 25 mm (SG2) and 50 mm (SG1) from the base. There is not only a resemblance in the pattern of the traces, but also in the duration of the oscillations observed. The delay in signals between the two positions is not as pronounced as when the bottle with a flat and rigid base is tested, since the distance between the positions is shorter. The shape is more triangular or sinusoidal than trapezoidal, which could support the dynamic character of the event, as in [7] (mass-spring model). However, this can also be attributed to a shorter valve-closure time, as explained earlier, causing the tendency to a triangular shape (waterhammer).

When the trace is compared to that of the bottle with flat and rigid base (Fig.9), it can be seen that the pressure rise rate is significantly affected; a strain rate of 4 s^{-1} is measured. The maximum pressure is around 40% lower than that measured when the base is flat. Two separate factors can be responsible: (i) the effect of base deformation and therefore slower water arrest on impact causes the tendency to a triangular shape; it has to be mentioned that the base of this container type has a very complex curved shape of a slightly bigger diameter than the rest of the bottle, and (ii) the imperfect impact between the rig and the floor, and the bottle and the rig; this double impact may prevent a square landing.

Fig.9 Comparison of the pressure histories for a bottle with and without base – 25 mm from the base

Tests with real bottles show that the base can have significant effects on the behaviour of containers subjected to drop impact not only on the pressure (stress) magnitude, but also on the shape of the histories recorded. Different base shapes affect the results in different ways, so the tests with a flat, rigid base are used to validate numerical procedures.

4.2 Numerical simulations

Figure 10-left shows simulated pressure histories from three monitoring positions, which correspond to the positions of a pressure transducer (PT) and two strain gauges (SG). The PT history is related to the pressure history from the middle base position. SG

histories are obtained from two positions along the bottle wall: 25 mm and 80 mm from the base. It is clear that all traces follow a similar pattern, the high frequencies being dominant only in the PT history in the first 1 ms.

Fig.10 Predicted pressure histories: left – all sensors, right – pressure history from the base

The effect of smoothing a simulated PT history by averaging over 100 points is shown in Fig.10-right. It can be seen that the high frequency oscillations are still present in smoothed trace, and some low-magnitude oscillations with a short period also remain. The latter have period of 0.9 ms and are related to natural oscillations of the bottle, as explained in the experimental part. On the other hand, the origin of the high frequency oscillations is not that clear. It was previously believed that these frequencies were of numerical nature caused by interactions on the solid-fluid interface (Greenshields *et. al.* [16]). However, detailed analysis of the pressure traces and pressure distribution in the fluid domain shows that they have a physical meaning, and are related to the presence of unconfined waves in the fluid, as explained below.

Figure 11 shows the pressure distribution in the fluid domain in the first 0.2 ms, with frame rate of 10 μs. The colours do not have the same values in the frames, since the figure is only used to clarify the origins of the high frequency oscillations in the pressure traces. The graph (at the lower right-hand corner) represents the pressure history at the middle of the base (lower left-hand corner of each frame). At the instant of impact, the fluid away from the wall has no information about wall movement and a wave starts travelling at the unconfined speed of 1485 m/s (= $\sqrt{K/\rho}$), producing a pressure magnitude of 41.6 bar (= $\rho \cdot c_{un} \cdot \Delta v$). This high pressure region is clearly visible in the middle part of the bottle base (frames 2 and 3). On the other hand, fluid particles next to the bottle wall start moving radially outward due to deformation of the wall. This fluid movement radiates a radial decompression wave towards the bottle axis. After approximately 30 μs ($D/2c_{un}$ =28μs) the wave reaches the axis (p<0 bar – frame 4), and produces the lowest pressure in frame 5.

Fig.11 Pressure distribution during first 200 μs – presence of unconfined wave speed

Meanwhile, the high pressure region continues to extend towards the top surface, followed by a low pressure region. It is clear from the first eight frames, *ie.* from the slope built up by the high pressure region, that they travel at the unconfined wave speed. The pressure at the bottom continues to oscillate due to radial waves. Therefore, two superimposed pressure oscillations travelling in different directions are present in the system immediately after impact. The situation becomes more complex when a compression wave travelling at the unconfined wave speed in the axial direction hits the top surface, returns to the base (frames 9 to 20) and meets the pressure waves travelling toward the top.

The highest pressure magnitude, as shown in Fig.10-right, taking into account only waterhammer pressure, is around 4.8 bar, which corresponds well with theoretical prediction and experimental results. The rate of pressure rise is difficult to calculate due to the significant influence of unconfined waves and will be investigated in strain histories, given in Fig. 12 for three different positions from the base. Unlike pressure histories, strain histories are very smooth, *ie.* without the superimposed high pressure oscillations. Clearly, the bottle is deformed as pressure travels through the system; firstly, the position nearest to the base is affected by the pressure rise, and then the other positions. The small `knees' observed at the beginning of the histories for all positions and consequent superimposed oscillations are due to natural oscillations of the bottle. The maximum strain in the first period is around 10 mstrains which is, when converted to pressure using a simple thin wall assumption, around 4.8 bar. The period of the main oscillation is 3.2 ms, corresponding to a wave speed of 156 m/s. All values are well predicted by the waterhammer theory. The strain rate can be easily calculated from the trace and value of 35 s^{-1} is obtained.

Fig.12 Predicted strain histories

Figure 13-left presents the pressure histories from the bottle wall at 25 mm from the base for four different drop heights. Results are related to those from experiments, given in Fig.7. Traces are self-similar, having the same pattern and period of the main oscillation, which is in agreement with waterhammer theory. Maximum pressure magnitude increases with drop height parabolically, and is in agreement with waterhammer predictions, as shown in Fig.13-right.

Fig.13 Predicted pressure histories from the bottle wall 25 mm from the base from different drop heights

Influence of the base shape on pressure and strain histories

To examine the influence of the base shape on pressure and strain histories, two different base shape geometries are considered: with a flat and flexible base, and with a curved and flexible base shape (Fig.14-left). The rest of the geometry domains are the same as in the cases with a flat and rigid base. In both cases the total number of cells for the fluid domain is 642, and for the solid domain 162.

Fig.14 Influence of the base shape: left - base shapes; right – predicte SG1 strain histories

Figure 14-right shows the influence of the base shape on the strain history in the bottle wall at the position 50 mm from the base. It can be seen that the loading rate is lower for the bottle with the originally manufactured curved base. This is caused by a gradual water stoppage due to deformation of the base as opposed to a sudden stop in the case of a bottle having a flat and rigid base. The shape of the first loading pulse is triangular, and slightly smaller in magnitude than in the case with a flat and rigid base. In addition,

subsequent oscillations are much shorter and smaller in magnitude, since the bottle has bounced. Similar behaviour is observed in the experiments (Fig.9).

4.3 Comparison between experimental and numerical results

Figure 15 shows a comparison between strain histories, at the position 25 mm from the base, obtained by numerical simulations and from the experiment for the case of a flat and rigid base with a drop height of 0.5 m. Strains from the numerical simulations are converted into pressures using thin-wall assumption. It can be seen that numerical prediction compares well with the experiment, having small differences in terms of strain rate in the pressurising stage, and in the behaviour after 1.7 ms. The first difference is related to the imperfectly square landing in the experiments, while an assumption of perfectly square landing was used in numerical simulations. The difference in behaviour after 1.7 ms comes from the minus 1 bar limitation in relative pressure, as the lowest possible pressure in reality, which is not incorporated in the numerical analysis, since it has no effect on container failure.

Fig.15 Comparison between experimental and predicted strain histories – 25 mm from the base

Comparisons between strain gauge history from the bottle wall 80 mm from the base and pressure history from the centre axis position at the base for numerical simulation and experiments are given in Figs.16-left and 16-right, respectively. Again, results agree well.

Fig.16 Comparison between experimental and predicted pressure histories: left – bottle wall, 80 mm from the base; right – pressure transducer at the base middle position

5. Conclusions

The analysis of experimental results demonstrates that there is a pressure wave travelling through fluid-filled containers subjected to the base drop impact. This is also supported by a sequence of a video-recorded drop impact test on RT6 containers, shown in Fig.17. These containers have a rectangular cross-section area, and thus more pronounced and noticable deformation. The presence of a pressure wave travelling can be seen from the ripples on the container wall: the container deforms progressively in time from the base towards the top due to the internal pressure wave. As the pressure wave reaches the top, the container wall is fully stressed by the internal pressure and the crack starts to propagate (image 19-20).

Fig.17 A sequence of the drop impact of the RT6 container – recording rate 4500 f/s

The period of the main oscillation in the pressure/strain histories, and its magnitude are well predicted by waterhammer theory. Maximum pressure magnitude follows a parabolic relationship to drop height. Natural oscillations are present in all results, and their period is in agreement with Eq.7. The shape of the container base significantly affects the pressure produced by the impact. This is mainly due to the base deformation caused by the impact. The water inside the container is gradually stopped, thus reducing the pressure (strain) rate and magnitude.

Results obtained from the two-system FSI simulations are found to be in good agreement with theoretical and experimental findings. It is clearly demonstrated that the pressure wave produced by the impact travels through the bottle, thus supporting the waterhammer theory. Pressure magnitude and the period of the main oscillation are also well predicted by the method. The maximum pressure of the main oscillation varies parabolically with drop height; the same was observed in experiments. It is also shown that the high-frequency oscillations in the pressure histories are not caused by numerical instability, but have a physical meaning - they are caused by the presence of unconfined pressure waves propagating in the fluid at high speed. The effect of the base shape on pressure/strain histories is also investigated. It is demonstrated that the curved base shape affects the pressure/strain pulse resulting in a more triangular profile of smaller magnitude.

It can be concluded, from experimental and numerical findings, that waterhammer theory explains the problem of the base drop impact of the fluid-filled containers better than the mass-spring model. The numerical results compare well with experimental observations. Hence, the two-system FVM numerical procedure applied shows a great potential for solving other impact problems involving fluid-filled bodies having complex geometries, such as side drop impacts, inverted drop impacts, crashes of reservoirs, and so on.

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Figure captions

Fig.1 A 1-litre bottle used to investigate drop impact of plastic containers – a) geometry b) geometrical and material data

Fig.2 Experimental set-up for instrumented drop impact test

Fig.3 Experimental rig: left – bottle without base; right – bottle with originally manufactured base

Fig.4 Numerical domain for the case with rigid and flat base

Fig.5 Pressure histories for bottle with flat and rigid base: left – all sensors, right – pressure transducer PT1

Fig.6 Pressure histories from the strain gauges

Fig.7 Strain gauge data from different drop heights: left – pressure histories, right – maximum pressure vs. drop height

Fig.8 Pressure histories for real bottle: left – all sensors, right – strain gauges

Fig.9 Comparison of the pressure histories for a bottle with and without base – 25 mm from the base

Fig.10 Predicted pressure histories: left – all sensors, right – pressure history from the base

Fig.11 Predicted pressure distribution during first 200 μs – presence of unconfined wave speed

Fig.12 Predicted strain histories

Fig.13 Predicted pressure histories from the bottle wall 25 mm from the base from different drop heights

Fig.14 Influence of the base shape: left - base shapes; right – predicted SG1 strain histories

Fig.15 Comparison between experimental and predicted strain histories – 25 mm from the base

Fig.16 Comparison between experimental and predicted pressure histories: left – bottle wall, 80 mm from the base; right – pressure transducer at the base middle position

Fig.17 A sequence of the drop impact of the RT6 container – recording rate 4500 f/s