MODELLING DROP IMPACT AND FRACTURE OF FLUID-FILLED PLASTIC CONTAINERS

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Abstract

Drop impact resistance of fluid-filled plastic containers is of considerable concern to plastics and containers manufacturers as well as distribution industries utilising containers for transportation of various liquids. This is due to potential failure of the containers following the drop impact and subsequent spillage of the transported liquid. In this work, a combined experimental-numerical study of the problem is presented. Experimental investigation was conducted on 1-litre cylindrical bottles made from polyethylene. Bottles were dropped from a given height onto a concrete floor, and pressure in the contained fluid was recorded during the experiment using pressure transducers. Numerical analysis was performed using Finite Volume based fluid-structure-fracture procedure. Here, Cohesive Zone methodology is introduced into the standard two-system solid-fluid coupling procedure to simulate and predict the failure process. It is shown that numerically predicted pressure and strain histories have good resemblance with experimental results.

Introduction

The basic aim in testing of the blow-moulded containers is to obtain their drop impact resistance. Different approaches are conventionally used to achieve this: standard drop test procedures (e.g. ASTM D2463-95), theoretical predictions (e.g. water-hammer, mass-spring theory, *etc.*), numerical simulations, *etc.*. The standard procedures provide a critical drop height above which a particular container will fail by using a statistical approach. The result of a single test is failure or non-failure. Containers of different shapes, sizes and material properties must be tested individually, making this approach very expensive in design optimisation, although very quick and useful in controlling the manufacturing process. On the other hand, application of the analytical predictions, i.e. pressure propagation, pressure distribution, *etc.*, is constrained to simple geometry and simple (*i.e.* linear) material behaviour. Thus, a properly validated numerical model is a useful tool to assist and accelerate product development, providing it includes an appropriate fluid-structure-interaction (FSI) model coupled with a failure model of the container material.

Experimental procedure and results

Experimental data (Karac [1]) were obtained on a set of 1-litre cylindrical polyethylene containers/bottles – referred to as SR1 bottles. Each container was further analysed after the testing, *i.e.* the thickness and density were measured at different positions of the container to obtain their variation. This is important since variations in material or geometrical properties

can result in local elevation of stresses, and thus failure initiation. It was found that the thickness varied significantly in both the axial and circumferential directions. These variations are result of the manufacturing process. However, they are repeatable for a production series with the same material grade and mould used. One can expect the thinner regions to be the weak regions, and consequently the regions of a potential failure (crack) initiation. On the other hand, density measurements at different positions have shown very little variation, i.e. less than 1%. Thus, the density was assumed constant throughout the container geometry. The modulus of elasticity was measured using standard tensile tests, and its variation was found negligible.

Containers were filled with water up to 210 mm and dropped from 4 m height using a specially designed drop impact rig (Fig.1). A bottle was positioned at the required height by a string that was fixed to the bottle cap at one side and a quick release mechanism at the other. The containers used in this study belong to a group of small blow-moulded containers. They are easy to handle and the deformation of the base due to the weight of the liquid content can be neglected. By activating the quick release mechanism, the bottle was released and dropped onto a concrete floor. Pressure in water was recorded at the central axis positioned 25 mm from the base using a pressure transducer placed in a length-adjustable pressure transducer holder. The holder was fixed to the bottle cap and immersed in water.

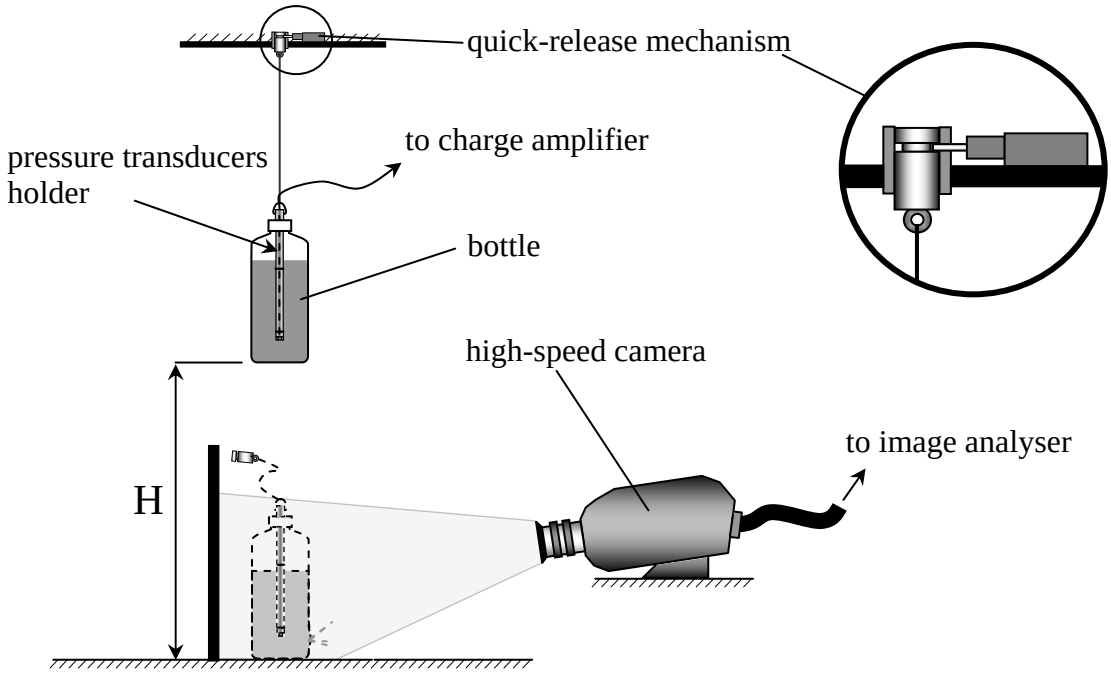

FIGURE 1. Drop impact set-up.

Typical pressure histories from tests with and without failure are shown in Fig.2-left. It can be seen that failure occurs during first pressure rise, at the instant when pressure magnitude reaches the critical value (around 6 bar). Fig.2-right shows the broken container. It can be seen that there is no global plastic deformation present, except in the narrow local region around the crack. In addition, the crack path is straight in the axial direction. Both findings are very important for subsequent numerical analysis, since bottle can be simulated using linear-elastic material model with prescribed straight crack path.

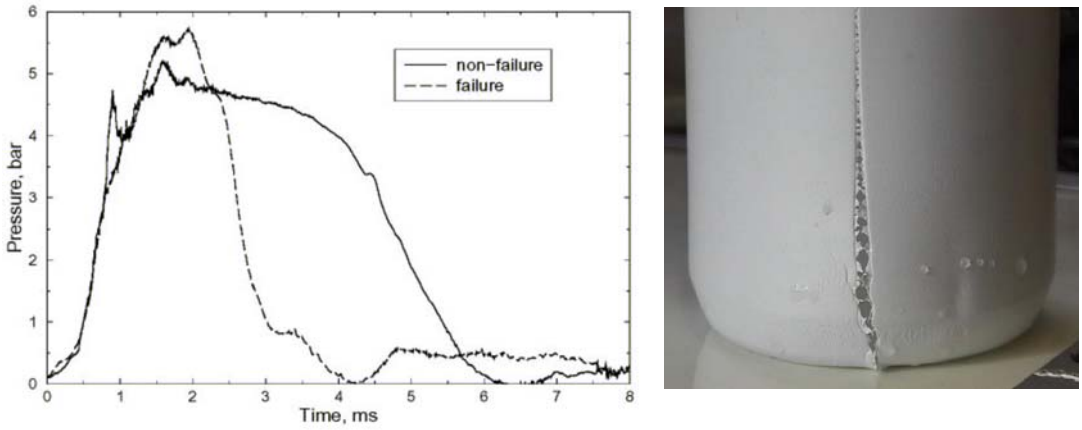

FIGURE 2. Drop impact of 1-litre bottle: left – pressure history, right – broken container.

3D FV fluid-structure-fracture procedure

Introduction

To model the failure of fluid-filled containers it was decided to employ the two-system fluid-structure interaction procedure (Greenshields *et. al.* [2], Ivankovic *et. al.* [3]). The main reason lies in the simplicity of the procedure when compared to the one-system procedure (Karac and Ivankovic [4]). Implementation of the fracture process into the one-system procedure requires special care of initially non-existing crack-gap and subsequent fluid escape through it: new cells have to be introduced to fill the newly created ‘empty’ space, which is not straightforward.

A schematic of the two-system fluid-structure-fracture (FSF) procedure is shown in Fig.3. It is implemented into a FV-based C++ library – Field Operation and Manipulation (FOAM) software [5]. The procedure is fairly straightforward: the fluid domain is solved first (by solving the momentum equation with the PISO pressure-velocity correction algorithm applied to the compressible fluid model), and the information from the fluid domain (tractions) is passed to the solid. Then, the momentum equation for the solid domain is solved, information about the contact with rigid impact surface and crack opening is updated, and necessary information from the solid (boundary velocity and crack opening geometry) passed to the fluid. For the implicit run, the aforementioned procedure is repeated within the time step until convergence, or until the maximum number of iterations within the time step is reached. In case of explicit procedure, the run is forwarded to the next time step after a single iteration.

There are two main differences between the two-system fluid-structure and fluid-structure-fracture interaction procedures. In the latter, potential crack propagation has to be simulated, and special care is needed for the information exchange between fluid and solid domains due to crack opening. This procedure had originally been developed to simulate rapid crack propagation in plastic pipes (Ivankovic *et. al.* [6]), and is adopted in the present work and further improved for the analysis of the drop impact problem (Karac and Ivankovic [7]).

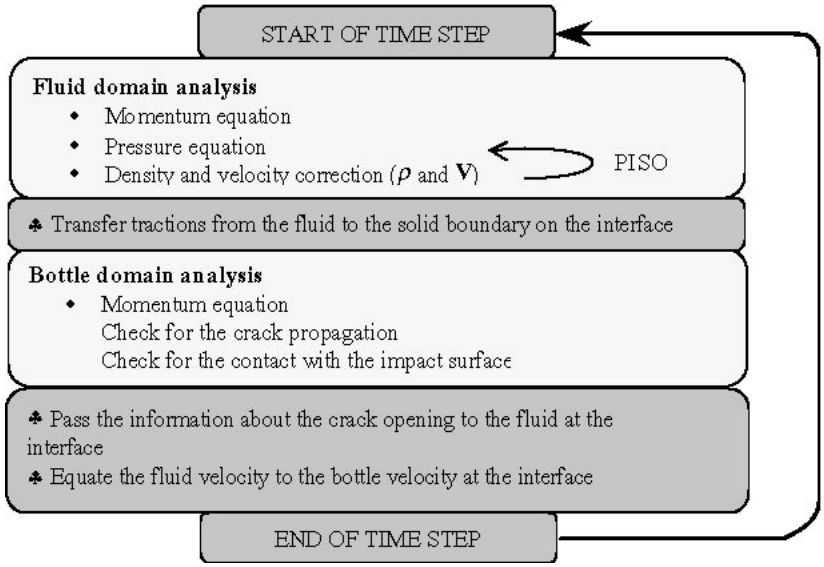

FIGURE 3. Schematic of the two-system fluid-structure-fracture procedure.

Modelling the failure process

The crack path, in general, is not known a priori, and can have an arbitrary shape (e.g. straight, curvy, wavy, with bifurcations *etc*.). In this study, however, a straight axial crack path is assumed and the boundary along which the crack will propagate is treated in a special way. As mentioned earlier, this assumption is based on the experimental observations. A fracture process is described by employing a local failure criterion represented by Cohesive Zone Model (CZM) or local traction-separation law. It gives a relationship between tractions holding the separating surfaces and the separation displacement between them. Crack initiation and subsequent growth can be determined directly in terms of CZM parameters: the strength of cohesion t_c, critical separation displacement δ_c, and the area G_D under the traction-separation curve representing the fracture toughness. The cohesive Zone parameters were obtained from conventional Essential Work of Fracture tests, as explained by Karac and Ivankovic [8].

It is worth pointing out that arbitrary crack paths can also be modelled within the FV framework, as described by Murphy *et. al.* [9]. The Cohesive Zone model is implemented at internal faces for cohesive cells in the cohesive region, so failure can follow any pattern between faces inside the cohesive region. Here, a special treatment of cell faces inside the cohesive region is required.

Information exchange at the fluid-structure interface

As the crack propagates and the container opens up, a special interpolation procedure is required to pass the appropriate information across the interface to the fluid. This is because the crack-gap appears and creates an escape route for the fluid, which is no longer fully contained. The developed model is capable of simulating flow of incompressible or compressible fluid through the crack gap, which is potentially smaller than the discrete boundary representation (cell face). The basics of the problem are shown in Fig. 4. Before the crack initiation, the solid and corresponding fluid boundaries at the interface coincide (Fig.

4a). The information exchange is straightforward; pressure is passed to the solid as traction, whereas the solid deformation is passed to the fluid as a velocity. The zero gradient boundary condition is used for pressure.

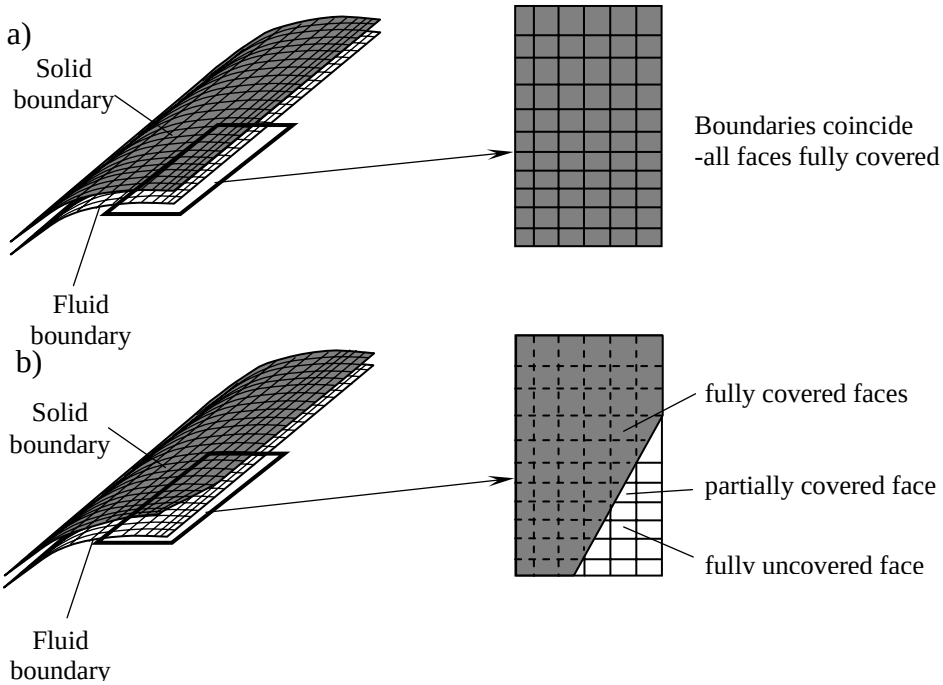

FIGURE 4. Information exchange at fluid-structure interface: a) before crack initiation, b) with crack propagation.

When the crack starts to propagate, a gap at the fluid boundary is created (Fig. 4b), and a special procedure is needed to perform the information exchange. To accurately capture the geometry of the crack and its influence on the flow field, irrespective of the resolution of the solid-fluid interface and without following the mesh lines of the fluid interface, three possible modes of interaction between fluid surface and fracturing container are considered:

- fluid cell-face fully covered with container,
- fluid cell-face fully uncovered,
- fluid cell-face partly covered.

Coupling of the first two modes is straightforward. The third one is treated as a combination of the covered and uncovered parts, each providing an appropriate contribution to the cell balance through a proportion of fixed-value (for covered part) and fixed-gradient (uncovered part) boundary conditions. This proportion is determined by calculating the (un)covered fraction of the face area. On the other hand, passing the pressure values from the fluid to the container wall at the interface was reasonably straightforward as all solid cell-faces on the interface were always fully covered by the fluid, and standard pressure interpolation sufficed.

Simulation of drop impact tests with subsequent failure

Problem definition and geometry domain

Numerical meshes for both fluid and solid domains of an SR1 bottle are shown in Fig. 5. Due to symmetry, a half of the bottle and water domains was modelled, considering only a part of the bottle in contact with water. This geometry corresponds to the SR1 bottle

geometry with a diameter of 82.44 mm and a length of 200 mm (*z*-direction). The thickness was assumed constant and equal to 0.72 mm; this value was calculated as an average of the measured thickness [1]. The solid domain was discretised into 8316 cells, with 3 cells through the thickness. The fluid domain consisted of 29664 cells. The mesh at the interface for both domains was identical.

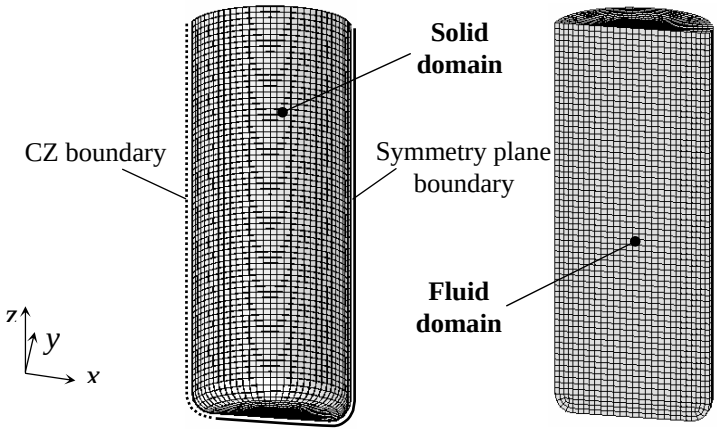

FIGURE 5. Computational mesh for solid and fluid domains.

The top part of the solid domains was modelled as a symmetry plane. Outer solid surface was traction free, except the base part, which was modelled using a direction mixed boundary condition, *i. e.* mixed condition (fixed-value/fixed-gradient) in the normal direction, and the fixed-gradient in the tangential direction, to allow the contact/bounce with the impact surface. Inner wall of the solid domain was modelled using a prescribed traction (passed from the fluid domain). Crack initiation and growth were simulated by means of Cohesive Zone model, where the cohesive zone boundary was represented with the help of direction mixed boundary condition along the prospective crack plane: dotted part of the bottle cross section as shown in Fig. 5. The crack is allowed to initiate at any point along this surface. The remaining part of the cross section was modelled as a symmetry plane.

The top part of the fluid domain (free surface) was modelled prescribing constant pressure and zero gradient for velocity, whereas the cross section was modelled as a symmetry plane. Surface at the interface was mainly modelled using a time-dependent fixed value boundary condition for the velocity and zero gradient for the pressure. In addition, a mixed boundary condition was used to model the region around the crack path in the fluid domain. This was to allow information exchange between the domains when the bottle fractures and water starts to `leak' through a gap created by the crack. This region should be big enough to cover the maximum possible crack opening, but not much bigger in order to minimise the CPU time due to the interpolation procedure in the information exchange algorithm. In the following simulations, this region was arbitrarily chosen to extend a third of the domain in the circumferential direction.

The bottle material was considered as linear-elastic. Thus, no global plastic deformation was accounted for in the simulations, which is in agreement with the observations from the base drop mode experiments on the SR1 bottles, as stated before. The fracture region was simulated using a Cohesive Zone model that accounts in a collective manner for all local damage/failure mechanisms including local plastic deformation and crazing. In this work, the Dugdale model was used in all simulations, although other more complex models can be easily applied.

The following materials' properties were used: 1) Solid (linear elastic Hookean solid): Young's modulus E = 0.7 GPa, Poisson's ratio ν = 0.32, density ρ = 948 kg/m^3, 2) Water

(Newtonian fluid): density ρ = 998.2 kg/m^3, bulk modulus K =2.2GPa, dynamic viscosity η =0.001 Pas. As for the cohesive zone model parameters, the craze stress t_c = 45 MPa and fracture resistance G_D = 15 kJ/m^2 were chosen, giving the critical crack opening displacement δ_c = 0.333 mm. CZM parameters were extracted from EWF tests as explained in [7]. Initial conditions included the drop impact speed of 8.8 m/s for both domains. Frictional effects were neglected. The computations were performed using a constant time step of 1 μs for both domains, and the solution was run for 8 ms or until failure occurred. Maximum number of coupling iterations was set to 20.

Pressure and strain histories were monitored at several positions in the fluid and on the bottle wall. Fig. 6-left shows the pressure histories in the fluid at an axial position 25 mm from the bottle base for two cases: without and with bottle failure. In the former case the failure was avoided by employing the symmetry plane boundary condition for the entire cross section surface. A comparison between the strain histories, expressed in pressure units, is given in Fig.6-right. Histories were obtained from the bottle wall at a position 25 mm from the bottle base next to the crack plane for the cases with and without bottle failure. It can be seen from both figures that histories follow similar pattern to that in the experiment (Fig.2); in both cases bottles behave in the same manner at the beginning of the pressurising period, but after 2.2 ms bottle with the cohesive boundary breaks under maximum pressure. Crack speed was also monitored, and an average value of about 500 m/s was obtained, compared with the value of about 300 mm/s observed in the experiments; experimental value was evaluated by processing the video recording. Crack initiated in the middle of the crack plane, *i.e.* 105 mm from the base. In the experiment, however, crack initiated around 40 mm from the base, where the bottle wall was thinnest. Simulations were stopped when the crack reached the top of the bottle.

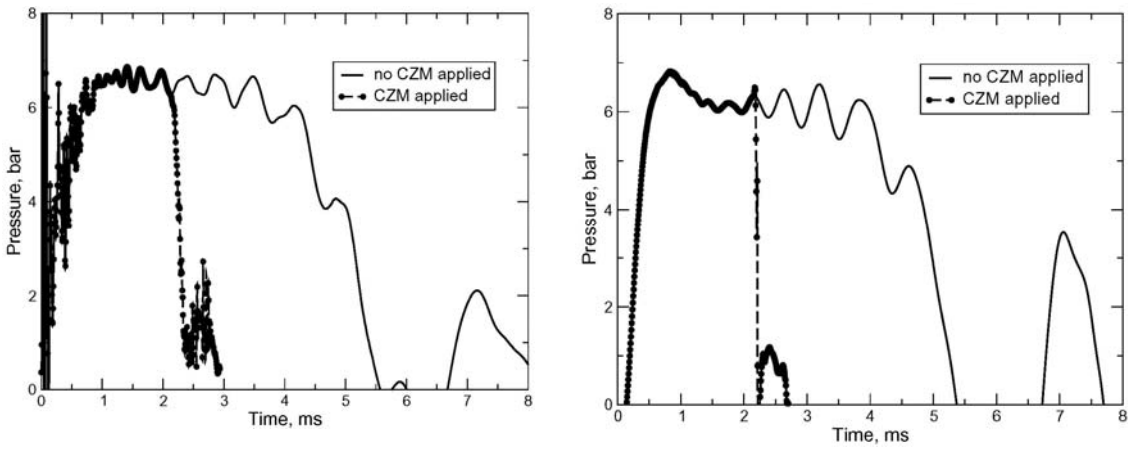

FIGURE 6. Results from numerical simulations: left – pressure history, right – strain history (strains are converted into pressure units)

Fig.7 shows the comparison between numerical and experimental results for the cases with (Fig.7-right) and without (Fig.7-left) failure. It can be seen that pressure magnitude is over-predicted in the numerical analysis, while the duration of the pressurised period agrees well with the experimental data. The differences between numerical predictions and experimental results are mainly due to the variation in the material properties and especially thickness of the real bottle, which was not taken into account in the numerical simulations. The inaccuracy in the numerically predicted crack speed is probably caused by the approximate cohesive zone parameters used along the fracture boundary. However, the overall behaviour is reproduced rather well, given the complexity of the problem.

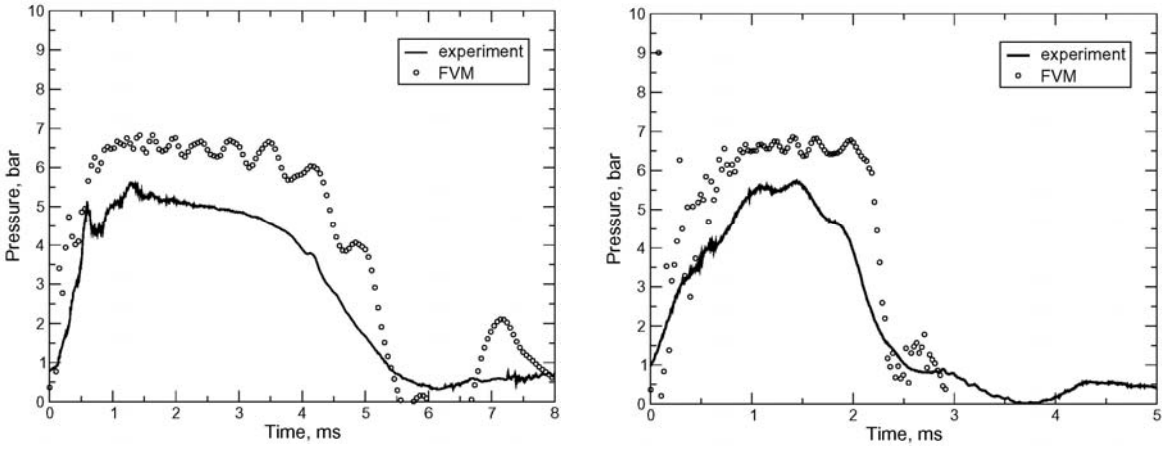

FIGURE 7. Comparison between the experiment and numerical simulation: left – non-failure test; right failure test

Summary

This work presented the application of the general fluid-structure-fracture code to drop impact of fluid-filled plastic containers. The model predictions in terms of pressure distributions, deformation and fracture were validated against experimental results. The complex coupling procedures as well as the failure model were verified. Given the appropriate material and geometry data, the model can be used for accurate, efficient and economical calculation of resistance of fluid-filled container under drop impact, and it represents a very powerful tool in design optimisation of plastic containers.

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