Impact on liquid filled containers

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Abstract

The study summarizes experiments and theoretical investigations to explore the behavior of liquid filled containers under medium speed impact. Thin-walled cylindrical steel containers with different wall thickness were impacted by gun projectiles. To investigate the major difference of the container failure modes empty and water filled containers were used. In the case of the water filled containers the impact damages ranged from simple perforation of front and rear wall to a catastrophic front wall rupture which started at the rim of the impact hole and an additional perforation of the rear wall. The development of the pressure distribution in the water starting at the point of penetration was followed through the container to the opposite wall and back to the point of entry of the projectile. Stresses and strains in the containment were registered. Also the impact velocity and the geometry of the container cause different failure modes. The primary and the reflected pressure fields interact with the wall creating specific crack patterns. Theoretical investigations by means of the Finite Element Method helped to explain the experimental findings.

1 Introduction

More and more highly dangerous liquids are stored in metal or concrete containers. Therefore impact owing to fast flying fragments caused by any kind of explosion or impact is of growing interest. Even if one vessel of a vessel battery cannot be designed against extraordinary loads like direct impacts, it is of importance to know the mechanism of fragmentation to prevent a chain reaction. The aim is to avoid impacts on the other vessels of the group owing to generated fast flying fragments. For a more suited design of containers against impact a better idea of the range of the different failure modes was developed.
2 Experimental investigations

In the range of an impact velocity of 380 to 733 m/s only a few comparable experiments using thin walled water filled steel containers exist. Experiments with low velocity impact with high masses - like the collision of a ship with a pipeline - or hypervelocity impact with small masses hitting tubes or vessels - like the collision of a meteorite with a gas cylinder - are not directly comparable to the discussed problems [1,4,7].

To study the principle behavior steel cylinders empty and filled with water were impacted by led projectiles of different velocities. The diameter of the cylindrical containers was 300 mm with a height of 600 mm and a variation of the wall thickness from 0.6 to 1.0 mm. The different projectiles had impact velocities of 380 to 733 m/s and a range of mass from 28 to 31 g. Strain gauges were used to measure the strains in the walls. The container walls with a thickness of 1.0 mm had a ultimate tensile strength of $R_m = 321$ N/mm$^2$, a yield strength of $R_{p0.2} = 150$ N/mm$^2$, a Youngs Modulus of $E = 199330$ N/mm$^2$ and an elongation at rupture of $A = 31\%$. Quartz pressure transducer put into the fluid was used to measure the pressure versus time. The whole process was filmed by high speed cameras. The experimental parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Wall thickness [mm]</th>
<th>Filling of the container</th>
<th>Impact velocity [m/s]</th>
<th>Kinetic energy [J]</th>
<th>Pressure transducer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beh.0</td>
<td>1.0</td>
<td>Water/Empty</td>
<td>384 / 380</td>
<td>2064 / 2021</td>
<td>No</td>
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<td>394</td>
<td>2406</td>
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<td>396</td>
<td>2431</td>
<td>Yes</td>
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<tr>
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<td>Water</td>
<td>421</td>
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<td>0.6</td>
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<td>420</td>
<td>2734</td>
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<td>8058</td>
<td>No</td>
</tr>
<tr>
<td>Beh.6</td>
<td>1.0</td>
<td>Empty</td>
<td>733</td>
<td>8328</td>
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</tbody>
</table>

The used pressure transducer can measure dynamic pressure fields with a maximum value of 200 bar. Because much higher values of maximum pressure were expected, the transducer was not used in the experiment Beh.5. The pressure transducer could only measure pressure fields coming from the front wall of the container, pressure fields coming from the rear wall were not measured. The pressure transducer was placed in the same vertical level as the impact point and horizontally 5 cm aside the impact point (see Figure 1). So it was placed 7 cm away from the front wall impact point of the projectile in total.
Figure 1: Construction of the containers used in the experiments Beh.1 to Beh.5.

Up to twelve strain gauges were fixed on each specimen to measure the strain versus time on different points of the container wall.

As previous tests at the institute had shown that the cracks in the container wall tend to expand in longitudinal direction the strain gauges were installed in circumferential direction to measure the maximum strain occurring.

Figure 2 shows on the left side the water filled container Beh.5 after the impact of a projectile with an impact velocity of 721 m/s. The front wall was ruptured over almost the total height of the container. On the rear side there was a whole where the projectile perforated the wall. On the right side of Figure 2 is the empty container Beh.6 after the impact of a projectile with an impact velocity of 733 m/s shown. On the front wall there is the perforation whole of the projectile. The rear wall of the empty container has also a perforation whole at about the same size like the front wall.
Figure 2: Left; Water filled container Beh.5 impacted by a 721 m/s fast flying projectile with a catastrophic front side rupture. Right; Empty container Beh.6 impacted by a 733 m/s fast flying projectile with front side perforation.

Figure 3 shows the results of the measurement recorded with the pressure transducer shown in figure 1. It takes about 0.048 ms before the primary pressure wave reaches the pressure transducer. Approximately $t = 0.15$ ms after the impact the projectile passes the pressure transducer. After that the pressure decreases.

3 Theoretical investigations

To explain the mechanisms involved in the front side rupture of fluid filled containers the process is split into several stages.

The following assumptions were made:

- The impact velocity is smaller (up to 720 m/s) than the speed of sound in the fluid (1485 m/s).
The container wall is thin compared with the diameter of the container filled with fluid.

Figure 3: Measured pressure in the water over time during the experiments Beh.2, 3 and 4. The inner figure shows a focus of the time where the projectile hits the front wall \((t = 0)\) until the primary pressure wave has passed the pressure transducer \((t = 0.11\text{ms})\).

When the projectile hits the container wall it first penetrates and deforms the container shell behind the impact point (see figure 4b). Combined with this process the impact generates a concentrated pressure wave in the fluid and perforates the container wall (see figure 4c). The primary pressure wave is then running through the fluid stored in the container with the speed of sound of the fluid. A second pressure field concentrates around the projectile pushing the particles of the fluid aside (see figure 4c and d). This circumstance causes the first major stresses and deformations in the nearby container wall. Depending on impact velocity, wall thickness and material of the container the crack initiation starts. The crack tip tend to run in longitudinal direction.

The primary pressure wave in the fluid reaches the rear wall of the container before the projectile arrives. The pressure wave is then reflected by the rear wall back to the front wall. Because the front wall is damaged already the incoming reflected pressure wave can cause the rupture of the whole front container wall. The perforation of the rear wall takes place after the rupture of the front wall, so it has no influence on that.
On the basis of the afore mentioned assumptions the circumferential stress $\sigma_\phi$ in the container wall is:

$$\sigma_\phi = p_{tot} \frac{r}{t}$$

(1)

Where $p_{tot}$ is the total pressure, $r$ the radius and $t$ the wall thickness of the container. Under the assumed circumstances the total pressure is composed out of two parts.

$$p_{tot} = p_D + p_V$$

(2)

where $p_D$ is the pressure caused by the projectile and the inward moving container wall which then generates a concentrated pressure wave in the fluid. The pressure $p_V$ is initiated by the moving projectile pushing the fluid aside. Both pressures are depending on location and time. Additional the pressure $p_D$ is a function of the impact velocity, the geometry of the projectile and on the density of the fluid. The pressure $p_V$ is a function of the material and thickness of the
container wall, the viscosity of the fluid and the impact velocity of the projectile. So eqn. (1) can be written as follows:

\[
\sigma_\phi = (p_D + p_v) \frac{r}{t}
\]  

(3)

Using a two-dimensional model with the Finite Element Program ABAQUS/Explicit the general behavior of a reflected pressure wave was simulated. The results are shown in figure 5.

![Simulation of a reflected pressure wave in a two-dimensional model generated with the Finite Element Program ABAQUS/Explicit.](image)

Figure 5: Simulation of a reflected pressure wave in a two-dimensional model generated with the Finite Element Program ABAQUS/Explicit.

4 Comparisation of the test results and FEM-Simulation

The whole phenomenon of a impact on liquid filled containers was simulated with the Finite Element Program ABAQUS/Explicit using a Lagrangian mesh.
The results of the measured strains in the experiment and the simulation are corresponding. Two examples of the comparison are shown in figure 6 and 7. The extreme deflections in the measurement results are caused by
electromagnetic influences. These deflections are of no account for the rest of the measurement.

Figure 8 shows a FE-Simulation of the pressure propagation in the fluid after impact with the primary pressure wave running through the fluid to the back side of the container (fig. 8a, b, c). 0.4 ms after the impact the reflected primary pressure wave reaches the front wall. Figure 8 shows also the pressure field caused by the projectile pushing continually the fluid aside.

Further FE-Simulations indicate that the ballistic limit depends on the wall thickness of the container and the filling. The ballistic limit of thin walled water filled containers is higher than that of empty once. On the other hand the ballistic limit of thick walled water filled containers is lower than that of empty once. This is caused by the failure mechanisms. Thinner walls tend to fail on impact by tensile fracture (dishing) and thicker ones by plugging at the impact place. The fluid in the container tend to prevent the dishing and supports the plugging failure. This may be the reason why Xiaoqing [6] came to different conclusions than Neilson [3] comparing the ballistic limit of empty and fluid filled tubes.

It was also found in a FE-Simulation that the material of the container has a big influence on the front side rupture. Low ductility of the material causes minor damping of the pressure fields at the rear side of the container, therefore the pressure fields are reflected more intensively. The low ductility and the more intensively reflected pressure fields tend to front side rupture.
5 Conclusions

First principle investigations have shown different failure modes for liquid filled containers. These failure modes are depending on mass and velocity of the projectile, and geometry and material of the container. This is a basis for ongoing work to explain also the failure behaviour of concrete containers due to its specific material features.

References


