Experimental and numerical study of water-filled vessel impacted by flat projectiles

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Abstract. To understand the failure modes and impact resistance of double-layer plates separated by water, a flat-nosed projectile was accelerated by a two-stage light gas gun against a water-filled vessel which was placed in an air-filled tank. Targets consisted of a tank made of two flat 5A06 aluminum alloy plates held by a high strength steel frame. The penetration process was recorded by a digital high-speed camera. The same projectile-target system was also used to fire the targets placed directly in air for comparison. Parallel numerical tests were also carried out. The result indicated that experimental and numerical results were in good agreement. Numerical simulations were able to capture the main physical behavior. It was also found that the impact resistance of double layer plates separated by water was larger than that of the target plates in air. Tearing was the main failure models of the water-filled vessel targets which was different from that of the target plates in air where the shear plugging was in dominate.

1. Introduction

Penetration and impact related problems have been an active research field for several centuries, and substantial effort has been devoted to this topic in experimental, numerical and theoretical investigations. Work on this topic has been reviewed by Backman and Goldsmith [1], Corbett [2]. Recently, Borvik et al. [3] conducted a series experimental and numerical investigations on the ballistic resistance of high strength steels and aluminum alloys to blunt and point-nosed projectiles. Impact can occur in on targets immersed in fluids other than air. Target-liquid interaction has been investigated by Lambert [4] for projectile velocities from 500 m/s to 10 km/s. Hydrodynamic ram effects on solid structures are an important aspect of underwater projectile propagation. However, relatively few reports exist concerning both perforation and interactions between the fluid and structures. In this paper, we carried out experiments on double-layered targets with the layers separated by either air or water. The double-layered targets were impacted by flat-nosed projectiles and the process was recorded by a digital high speed camera. A series of numerical simulations were conducted by using coupled Lagrange-Euler methods in the AUTODYN-3D package. Details of perforation process and fracture characteristics of targets were addressed.

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2. Experiment and results

2.1. Experiment
The target was a vessel, consisting of 3mm thick plates of 5A06 aluminum alloy held by a high strength steel frame. The size of the target plates is 290 mm × 295 mm and two opposite sides of the plate were fixed into two rigid beams, with an unsupported areas of 250 mm × 155 mm. Target configuration includes: 3+300+3 mm double-layered targets (DLTs) separated by 300 mm water; another condition is 3+300+3 mm DLTs separated by 300 mm air. The solid cylinder projectiles of 12.62 mm × 38.1 mm are made from 38CrSi high strength steel. All the experiments were conducted with a two–stage light gas gun system. The initial impact velocity was measured by a lasers interrupt system. A sketch of the experimental set-up is shown in figure 1.

2.2. Experimental results
Figure 2 shows the impact process at \( v_i = 377 \) m/s when the plates are separated by air. As seen, the projectile perforates the first plate by shearing a plug of material. The plug of plate material travels ahead of the projectile. After crossing the 300 mm air gap, the plug impacts the second plate, after which the projectile impacts the plug. Subsequently, as a single body, the projectile and plug perforate the second plate (case I), forming a second shear-bounded plug. The second plate target is severely deformed, becoming convex out (i.e., downrange). However, there are also cases where plug formed during penetration of the first plate does not travel in the impact trajectory due to the projectile’s non-normal impact on the first plate or non-symmetric deformation and fracture of the first target. There are two cases, i.e., the projectile penetrates the second plate alone (case II) and the projectile with partially overlaps the plug and the combination of the two penetrates the second target (case III). For case II, the second plate will suffer from perforation by formation of a shear-bounded plug of material, while for case III the large deformation and plug formation during penetration both occur. For the last two cases, the second plate will suffer much more structural deformation, which will absorb more energy, as pointed out in [3].

The initial-residual velocity curves for this configuration target plates are shown in figure 3, the fitted curves are from the analytical model originally proposed by Recht and Ipson [5]

\[
\begin{align*}
    v_r &= a(v_i^p - v_{bl}^p)^{1/p},
\end{align*}
\]

where \( v_i \) and \( v_r \) are the initial and residual velocity of the projectile, respectively. Residual velocity is the final velocity of the projectile after it exits the air-filled vessel. \( v_{bl} \) is the ballistic limit while \( a, p \) are model constants. The related parameters of fitting curves are listed in table 1.

| Table 1 Model parameters for fitting curves. |
|----------------------------------------------|
| \( v_{bl-I} \) (m/s) | \( a_I \) | \( p_I \) | \( v_{bl-II} \) (m/s) | \( a_{II} \) | \( p_{II} \) |
|----------------------|--------|--------|----------------------|--------|--------|
| 361.52               | 0.58   | 4.62   | 265.09               | 0.62   | 3.27   |
Figure 2. Impact process for 3+300+3 double-layered targets separated by air at $v_i=377.0$ m/s.

Figure 3. Initial versus residual velocities when DLTs separated by air.

Figure 4 shows the impact process for a projectile velocity of 413.5 m/s into a water-filled target. In figure 4 (a) the projectile penetrates the first target plate. Figure 4 (b) and (c) show the trajectory of projectile in the water after perforation of the first plate, including cavitation behind the projectile. The maximum deformation of the second target plate was observed at about 3.538 ms. The expansion and collapse of the cavity in the water behind the projectile can be seen in the series of images presented. After 0.138 ms, the projectile has penetrated the first plate and there is a small volume cavity behind the projectile. The cavity grows toward the second target plate along the projectile trajectory with time [see figure 4 (a-d)]. After 1.378 ms the cavity starts to shrink and completely collapses [see figure 4 (e, f)].

Figure 4. Impact process for 3+300+3 double-layered targets separated by water at $v_i=413.5$ m/s.
3. Simulation and results

3.1. Numerical model and material behavior

The experiments were simulated using coupled Lagrangian-Eulerian hydrocode calculations in the AUTODYN 6.1 software package in order to study the main processes active during impact and penetration of the water-filled vessel. 3D models were constructed for all configurations involved. The coupled Lagrange-Euler technique was used to build the interactions among water, projectile and target plates, respectively. The projectile, water-tight vessel and target plates were modelled as Lagrange parts, and the water was modelled as Euler part. All parts of the 3D model were built with transition mesh.

The mechanical behavior of 38CrSi was modelled as a bilinear elastic-plastic von Mises material with isotropic hardening. The material constants for 38CrSi were assumed to be the same as that of the projectile used in [6]. Johnson-Cook strength and fracture criterion were used to for 5A06 aluminum alloy. To be able to describe the various phenomena taking place during the impact process, it is necessary to characterize the material behaviour of target plates under high strain rates. Thus, a series of material tests were performed on 5A06 aluminum alloy specimens. The true stress-strain curves of 5A06 aluminum alloy obtained from quasi-static and high strain rate compressive tests are presented in figure 5. It indicates that increasing dynamic strain rates tends to mildly increase the flow stress of specimens. Details regarding the mechanical properties tests, results and calibration procedure are given by reference [7].

Here, only the main results are showed. A slightly modified Johnson-Cook strength mode is used to describe the hardening, strain rate effects. It reads

\[ \sigma = (A + B\varepsilon^m)(1 + f(\dot{\varepsilon}^*)\ln(\dot{\varepsilon}^*)(1 - T^m)), \]

where \( \varepsilon^* \) is the dimensionless strain rate, \( T^* = (T - T_r)/(T_mB - T_r) \) is the homologous temperature. And \( f(\dot{\varepsilon}) \) reads

\[ f(\dot{\varepsilon}) = 10^{-5}\dot{\varepsilon}^{0.6}. \]

The related material parameters of 5A06 aluminum alloy and 38CrSi are listed in table 2. The software provided EOS model was used for water.

![Figure 5. The stress-strain curve of 5A06 aluminum alloy.](image)

| Table 2 Material constants for 5A06 aluminum alloy and 38CrSi. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                |                |                |                |                |                |                |
| \( E_{\text{aluminum}} \) (Gpa) | \( \rho_{\text{aluminum}} \) (kg/m³) | \( A \) (MPa) | \( B \) (MPa) | \( n \) | \( m \) | \( T_r \) (K) | \( T_m \) (K) |
| 69.30           | 2830            | 168.4          | 950.5          | 0.71          | 1.08          | 293            | 853            |
| \( E_{\text{38CrSi}} \) (Gpa) | \( \rho_{\text{38CrSi}} \) (kg/m³) | \( v_{\text{38CrSi}} \) |
| 204             | 7850            | 0.33           |
3.2. Simulation results

The final damage modes of the target plates separated by air are showed in figure 6 for an impact velocity of 327.0 m/s. As seen, both the plates of the target failed by formation of a plug bounded by shear surfaces, although deformation of the second plate is substantially greater. As shown, the simulation results are quite close to the test results. The ballistic resistance of the targets for case II is much lower than that for case I. The simulation results are plotted in figure 2. The ballistic limit for DLTs in air approaches 361.0 m/s and 267.5 m/s for case I and II, respectively. The ballistic resistance of the targets for case II is much lower than that for case I. The above reason stated above for the large divergence ballistic resistance of DLTs in air is supported by these results.

![Figure 6. Post-test photographs of DLTs separated by air.](image1)

Post-test photographs of the DLTs divided by water are shown in figure 7. The specimens were subjected to projectile of initial velocity \( v_i = 413.5 \) m/s. As seen, both the double layer plates have large deformation, and most of the deformation of the target plate take place after the projectile enters into the water-filled tank [see figure 4]. The projectile perforates the first plate by shear plugging and then the ejecting plug travels ahead of the projectile. After traveling the water-tight tank, the plug impacts the second target plate before the projectile impact it. The second target plate was torn as a result of the effect of the ram pressure in the liquid.

![Figure 7. Post-test photographs of DLTs separated by water.](image2)

Figure 8 shows the projectile velocity attenuation during the impact process. As seen, in addition to the resistance of two plates, the water between the two plates also contributes to the projectile velocity loss, i.e., the water cause velocity loss of nearly 85 m/s. Thus, from the limited study, it is
reasonable to conclude that the 3+300+3 mm DLTs separated by water would be more resistant to blunt projectiles impact than the corresponding targets in air due to the resistance from water between the two plates.

**Figure 8.** Current travel velocity versus time.

### 4. Summary

The failure modes of water-filled and air-filled vessels impacted by flat-nosed projectiles were investigated by experimental tests and numerical simulations. From the limited study, it is concluded that the ballistic resistance of double-layered plates separated by water would be higher than that placed in air due to the additional resistance offered by the water between the two plates. In addition, the double-layered plates in air concerned failed by formation of plugs bounded by shear surfaces. The plates of water-filled vessel have a large of deformation as a result of the effect of ram pressure in the liquid, and the second target plate was torn after the projectile perforated it.

### 5. References

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