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Numerical Modeling of the Ballistic Limit in the Hydrodynamic Ram

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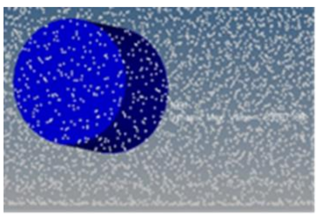
Graphical abstract



Abstract

This paper presents the ballistic limit study for the water-filled aluminum tank. The objective was to determine the ballistic limit for the rear tank wall by using numerical method. Commercial software Altair Hyperworks 12.0 was employed for this study. The finite element coupled with smoothed particle hydrodynamics (SPH) was developed to model the perforation of fragment simulating projectile (FSP) towards water-filled tank. Verification of the results was done by comparing with the experiment results. The results showed that there were four main phase failures occurred, which were shock phase, drag phase, cavitation phase and exit phase. The ballistic limit for the rear wall was 479.27 m/s.

Keywords: Ballistic limit (BL), hydrodynamic ram (HRAM), fragment simulating projectile (FSP), smoothed particle hydrodynamics (SPH)

1.0 INTRODUCTION

The ballistic limit (BL) also known as V_{50} is characterized by the velocity that has capability of perforation the target 50% [1]. Deng Yunfei *et al.* (2014a) conducted experiment of the BL for double layered steel plates. It was impacted by blunt and ogival nose projectile which launched by a gas gun. They found that the BL was higher for the upper layer with high strength and low ductility material and lower layer with low strength and high ductility material compared with the opposite arrangement of the layer [2]. Deng Yunfei *et al.* (2014b) investigated the BL for the monolithic, double- and three-layered steel plates. They observed that monolithic plates had higher BL compared with multi-layered plates when impacted with low strength of projectile, regardless of nose shape. In addition, the BL decreased with the increase of layers of plate [3]. MR Aziz *et al.* (2013a, 2013b and 2015) [4, 5 and 6] and MR Aziz *et al.* (2014a and 2014b) [12 and 13] conducted study on the BL for the empty aluminium tank which was impacted by fragment simulating projectile (FSP). Terminal ballistic which was sub-topic in the BL was discussed in their articles. Numerical simulation showed good agreement with the experiment results.

Hydrodynamic ram (HRAM) occurs when a high kinetic projectile perforates a tank contained fluid. The momentum and kinetic energy from the projectiles is transfers to the fluid surrounding the tank which lead to the risk of failure and structural damage [7]. D. Varas *et al.* (2011) conducted numerical simulation of partially filled aircraft fuel tanks by using LS-DYNA software. The objective was to fill the gap for the partially filled tank since many researchers concentrated on the completely filled tank. They claimed they had succeeded reproduced the stages of the HRAM in partially filled tubes from a qualitative and quantitative angle [8]. Peter J. Disimile *et al.* (2011) investigated the mitigation of shock waves in the water filled tank to gain the pressure generated by the HRAM. They found that the initial pressure wave and the cavity collapse pressure were due to the back wall pressure. By optimized the shock mitigation member, the effect of HRAM can be reduced [9].

Smoothed Particle Hydrodynamics (SPH) is a system pioneered by Lucy (1977) and Gingold and Monaghan (1977) to solve astrophysical issues. It is a system based on a set of particles which each of particle has their own properties and behaves according to the governing equations. SPH has been enhanced to explore dynamic response of strength of material and fluid flows. Among advantages offered by SPH are its ability to simulate excessive deformation, breakage, high velocity impact and manufacturing processes (Yongqiang Chen and Sivakumar Kulasegaram, 2009) [10]. Marco Anghileri *et al.* (2011) carried-out simulation of SPH for the rigid body water impact. The research was initiated due to aircraft accident such as helicopter ditching which leads to the tragic consequences. They concluded the SPH simulation was able to simulate well the experiment approach [11].

From the literature reviews, there were only a few cases involved cross-field between all these three major researches. The authors intended to combine these entire three major researches into one topic which was the ballistic limit for the hydrodynamic ram case by using smoothed particle hydrodynamics method.

2.0 TENSILE TEST

The tensile test was conducted according to Standard Test Methods for Tension Testing of Metallic Materials (2012) [14]. Since the aluminium was received from supplier, therefore it was important to determine the Young's modulus, Yield strength and Ultimate strength of the tank. These values were needed to utilize during the numerical simulation set-up. For the tensile test, the cross-head speed was set to 2 mm/min, 5 mm/min, 8 mm/min, 10 mm/min and 12 mm/min. This to ensure the yield strength obtained was accurate. Universal Testing Machine Shimadzu 50 kN was employed for this test. The data obtained from the test was processed by using Trapezium II software. In order to determine the value of Young's modulus, 0.2% offset yield method was employed. By taking the average, the Young's modulus, Yield strength and Ultimate strength was equal to 70 GPa, 306 MPa and 364 MPa, respectively. It was believed the tank material was Aluminium Alloy 6082-T6.

3.0 NUMERICAL SIMULATION SET-UP

Commercial software Altair Hyperworks 12.0 was employed for the numerical simulation. For the pre-processor, processor and post-processor purpose, HyperMesh, RADIOSS and HyperView were employed, respectively. The tank was modeled with 750 mm long, 3 mm thick and 150 mm wide by using 2D elements. There were two sizes of mesh used, which were 10 mm x 10 mm and 0.5 mm x 0.5 mm as shown in the Figure 1. The main reason two sizes of mesh were used because the impacted area required finer mesh for a better result. The whole tank was not using 5 mm x 5 mm because of the time consumed during the simulation. The side of the tank was not meshed because it did not involves the perforation process by the FSP.

Meanwhile for the FSP, it was modeled by using 0.5 mm x 0.5 mm with 2D elements as well. It had 6 mm height and 5 mm diameter. FSP was modeled as rigid body since there was no interest on what happened to the FSP during and after the perforation. A rigid body is an unchanged structure and developed by a set of slave nodes and a master node. Commonly the master node is shifted to the center of mass. The main focus was on the tank and also water. Figure 2 shows the completed rigid body of the FSP.

For the water, a dummy rectangle needed to be done first. Then, the water was modeled with SPH option. The distance between the particles equal to 1 mm. Figure 3 shows the water created by using SPH. The density of the water was set to 1000 kg/m3.

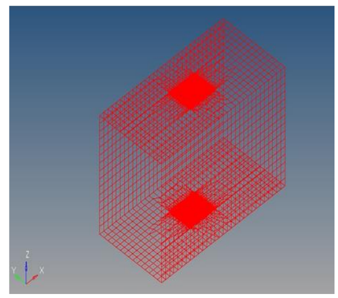


Figure 1 Isometric view of the tank

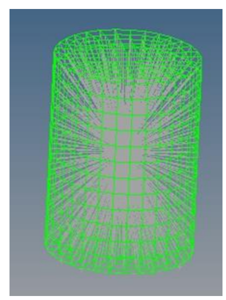


Figure 2 The completed FSP

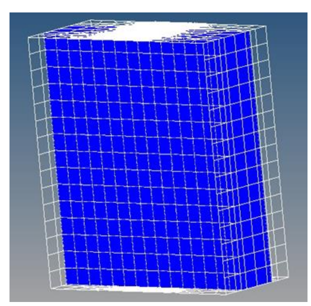


Figure 3 Water by using SPH

The tank property was obtained from the tensile test conducted. For the tank, it was assigned with M2 material, which was an isotropic elastic-plastic material that employed Johnson-Cook material model. The stress-strain relation was given by the following equation:

$$\sigma = (a + b\varepsilon_p^n)(1 + c.\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}})(1 - T^{*m}) \qquad \text{(Eq. 1)}$$

where σ is the stress level, ε_p^n is the plastic strain, a is the yield stress, b is the hardening modulus, n is the hardening exponent, c is the strain rate coefficient, $\dot{\varepsilon}$ is the strain rate and $\dot{\varepsilon_0}$ is the reference strain rate. The first bracket on the right hand side of the equation represents the influence of plastic strain. The second bracket and third bracket represents the influence of strain rate and the influence of temperature change, respectively. For this simulation, failure criterion based on the maximum plastic strain, εmax and maximum stress, σmax were added. For the FSP, it was modelled by using material M1, which was for elastic material. It was for an isotropic and linear elastic material using Hooke's law. This law represents a linear relationship between stress and strain. Only three parameters involved i.e. the density, Young's modulus and Poison's ratio. All these information were obtained from the MIL-P-46593A (ORD.) (1962) [15]. Table 1 shows the material properties for the tank and projectile.

Table 1 Material properties

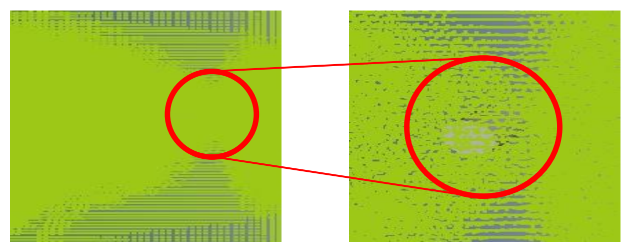
	ρ	**E**	**υ**	**a**	**b**	**n**	**ε_{max}**	**σ_{max}**
Tank	2770 kg/m³	70 GPa	0.35	306 MPa	71 MPa	7.65e-2	0.35	364 MPa
Projectile	7861 kg/m³	205 GPa	0.29	-	-	-	-	-

4.0 RESULTS AND DISCUSSION

4.1 Validation of the Simulation

The velocity of the FSP was influenced by the amount of charge weight that was put into the bullet jacket. The maximum velocity was 972 m/s and FSP had failed to perforate the rear wall [5]. Thus, the simulation which had same parameter as the experiment has been carried-out. Figure 4 shows the comparison of the terminal ballistic of the FSP both by experiment and simulation. Note that the tank was hidden in the figure. It can be seen clearly that when the FSP about to impact the rear wall, bounce wave occurred. Afterwards, the FSP merely touch the rear wall. The velocity at the last frame, which was at Frame 134, the velocity of the FSP was 83.07 m/s as shown in the Figure 5. That velocity was too slow to perforate the rear wall. Generally, good agreement was achieved between the experiment and simulation.

(a) Experiment footage



(b) Simulation

Figure 4 Bounce wave

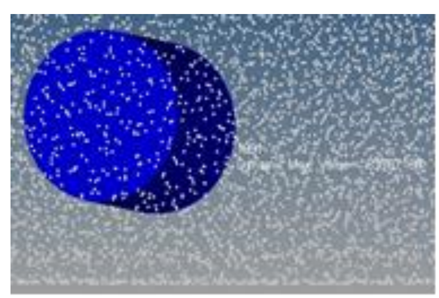
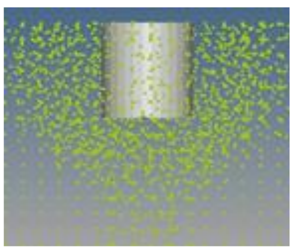


Figure 5 Last frame of the velocity 972 m/s

4.2 Main Failure Phase

Figure 6 shows the four main phases during the hydrodynamic ram phenomenon which each phases represent different damages to the structure (tank). Tank was hidden in this figure. In the first place, when the FSP impacted the tank and perforated the front wall, the kinetic energy and impact energy was transferred to the water in the tank. Consequently, high pressure of hemispherical hemispherical shock wave developed. As a result, damage occurred at the surrounding of the impact point. This phase was known as shock phase. The second phase was the drag phase. In this specific phase, the FSP travelled through the water. The kinetic energy was partially transferred to the water motion and therefore the FSP velocity became lower due to the water drag forces. There was radial pressure field developed and a cavity behind the FSP as the FSP displaced the water. The third phase was the cavitation phase. During this phase, there was subsequent expansion of the cavity as the FSP travelled towards the rear wall. The oscillations of the cavity might cause drastic pressure wave. Lastly was the exit phase.The FSP exit the rear wall that has been stressed by the shock phase and pressure from the water [9].



(a) Shock phase

(b) Drag phase

(c) Cavitation phase

(d) Exit phase

Figure 6 Failure Phase in HRAM

4.3 Ballistic Limit

As mentioned above, when the FSP was set to initial velocity of 972 m/s, it was failed to perforate the rear wall. Both were observed thru experiment and simulation. Since the experiment had constrained with velocity of FSP, the further investigation was conducted by simulation only. The FSP eventually perforated the rear wall when the initial velocity was set to 2000 m/s. Just before the FSP impacted the rear wall, the velocity was 479.27 m/s as shown in the Figure 7. This velocity similar with the experimental velocity, which was 480.93 m/s [6]. Even though the initial velocity was set to 2000 m/s, but as the FSP travelled through the water, the velocity had decreased. Nevertheless, when the FSP impacted the rear wall, it has sufficient velocity for perforation.

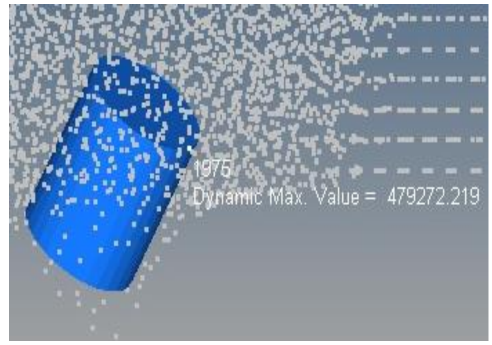


Figure 7 The rear wall perforation

5.0 CONCLUSION

The ballistic impact study for the water-filled aluminum tank has successfully conducted. There were four main phases observed i.e. shock, drag, cavitation and exit phase. The ballistic limit for the rear wall was 479.27 m/s.

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