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Effect of blast and gas pressure on debris launching velocity under internal detonation

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Abstract

Debris launching velocity is one of the major parameters in determining the debris hazard zone caused by accidental detonation of ammunition in a magazine. Upon detonation, the explosive generates a blast pressure. In tandem, gas pressure is also created due to accumulation of the gaseous products with high temperature produced by the explosion. It may cause the structural breakup and then exerts impulse on the debris. The impulse makes debris fly with an initial velocity. Subsequently, the pressure propels the debris to fly faster and accelerate until the overpressure (over the ambient pressure) drops to zero. After that, the debris continues to fly but slows down due to the frictional drag by the surrounding air. This paper presents a study to differentiate the effects of blast pressure and gas pressure on the debris launching velocity. Numerical simulations for a series of defined cases under different conditions are carried out. To begin, two basic and extreme cases are investigated. The first case is to detonate the explosive put inside a fully-constraint cubicle to evaluate the gas pressure. The second case is to detonate the explosive in an open space to evaluate the blast pressure. Then, a typical setup is used to evaluate the debris launching velocities under the effects of both blast pressure and gas pressure. In the numerical simulations, the high explosive (HE) and the air are modeled using Arbitrary-Lagrangian-Eulerian (ALE) multi-material formulations while the fluid-debris interaction is simulated via coupling techniques for fluid-structure interaction (FSI). Simulation results yield relatively good agreement with those obtained from experiments and empirical equations. It provides insight and explanations for the debris launching process which is hardly observed in the experiments. This study verifies the different effects on the resulting debris launching velocity due to the blast pressure and the gas pressure. It also shows that the gas pressure has dominant effect on the debris launching velocity.

Keywords: Debris, internal detonation, gas pressure, blast pressure, launching velocity, fluid-structure coupling

1. Introduction

The debris dispersion pattern resulting from an internal accidental explosion of a magazine is a major concern for the design, in particular the site selection criteria for an explosive storage magazine. It has been recognized that the resulting debris throw from a broken-up reinforced concrete magazine structure is complicated. Facing this challenge, the Klotz Group set up a long-term program to develop a predictive tool for the debris dispersion pattern resulting from an accidental internal detonation of ammunition storage in a reinforced concrete magazine structure. Other than the debris mass/size, the launching velocity is another major parameter required to determine the hazardous energy level and thus the debris hazard zone. Klotz Group has carried out a series of Debris Launching velocity (DLV) tests [1-2] to determine the launching velocity amongst different parameters. Theoretical solutions for some scenarios are also available [3-4]. In this paper, a series of numerical simulations for a variety of
cases under different conditions are carried out. It is to understand the mechanism that creates the debris launching velocity (DLV), with focus on the propelling power derived from the blast pressure and the gas pressure. The numerical simulations not only lower the cost of field tests, but also enable clearer understanding of the mechanism, which would help interpret the data/observations obtained from a full simulation of a magazine structural break up and the subsequent debris dispersion due to an internal detonation.

When an internal explosion occurs in a magazine structure, the initial blast shock pressure is extremely high and subsequently it will be amplified due to wave reflections within the enclosed structure. In tandem, additional pressure is created due to accumulation of the gaseous products with high temperature produced by the explosion, known as ‘gas pressure’. It may cause the structural breakup and then exerts impulse on the debris. The impulse makes the debris fly with an initial velocity. Subsequently, the pressure propels the debris to fly faster and accelerate until the overpressure (over the ambient pressure) drops to zero. This paper presents a study to differentiate the effects of blast pressure and gas pressure on the debris launching velocity. Numerical simulations for a series of defined cases under different conditions are carried out. To begin, two basic and extreme cases are investigated. The first case is to detonate the explosive put inside a fully-constraint cubicle to evaluate the gas pressure. The second case is to detonate the explosive in an open space to evaluate the blast pressure. Then, a typical setup is used to evaluate the debris launching velocities under the effects of both blast pressure and gas pressure.

2. Summary of DLV tests by Klotz Group

The test arrangement was a massive, subsurface 1 m³ cubicle chamber and the test object rested on top of the detonation chamber in a free body position without any clamping. The test objects were square plates, steel or reinforced concrete with 3 different masses: 120 kg/m², 240 kg/m² and 480 kg/m². The hemispherical HE Pentolite charges with 0.125 kg to 16 kg is detonated at the fixed distance R=0.5 m right below the slab center. High speed video camera was used to measure the slab velocity. Fig. 1 shows the DLV test arrangement. [1]

![Fig.1 Schematic diagram for the Debris launching velocity (DLV) test arrangement](image)

3. Numerical simulations

In the numerical simulations, the mass of the test slab is 240 kg/m². It is a steel plate and equivalent to 0.1 m thick reinforced concrete. Just following the DLV test, the Pentolite charge is 1 kg of hemispherical shape, and thus the loading density is 1 kg/m³.

3.1 Arbitrary-Lagrangian-Eulerian (ALE) multi-material formulation

Explosion by high explosive is a very complicated physical phenomenon. Numerical modeling of explosive detonation and expansion are difficult if the classical Lagrangian finite element approach is adopted. Lots of recent research works have proved that the Arbitrary-Lagrangian-Eulerian (ALE) multi-material formulations can simulate the high explosive phenomena more effectively [5-6]. In the simulation of explosion process, an element may contain one or two different material, air and gas production. An interface-tracking algorithm is used to detect the interface of two different materials in the same element. ALE multi-material formulation allows the material flow in the mesh with the mesh.
remained original shape. It is used in the present simulations for blast loading analysis.

The explosive loading exerted onto the structure is implemented via a fluid-solid interaction (FSI) algorithm. In the computer code, this interaction is controlled by a mechanism between a slave Lagrangian geometric entity and a master Eulerian geometric entity. In this study, the penalty-based FSI coupling is adopted to effectively simulate the interaction between the solid and fluid parts. The solid part including the slab is modeled using the Lagrangian formulation. The fluid part including air and HE is modeled using the Eulerian multi-material formulation with the element formation 1-point ALE multi-material element [7].

3.2 Material models for air and explosive

The air is modeled as an ideal gas using hydrodynamic material model, which is defined by parameters including density ($\rho$), pressure cut-off ($P_C$), viscosity coefficient ($\omega$) and a linear polynomial equation of state (EOS). The EOS describes pressure-energy-density ($P$-$E$-$\rho$) relationship as follows:

$$P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2)E$$

(3.1)

in which $C_0$, $C_1$, $C_2$, $C_3$, $C_4$, $C_5$ and $C_6$ are empirical constants, and

$$\mu = \frac{\rho}{\rho_0} - 1$$

(3.2)

where $\rho_0$ and $\rho$ are the initial and current densities of air.

The explosive detonation is simulated using a burn model which is defined by parameters including density ($\rho$), detonation velocity ($V_D$), Chapman-Jouguet pressure ($P_{CJ}$) and an equation of state. Here, we adopt the widely used Jones-Wilkins-Lee (JWL) EOS which is known to be a satisfactory model for most high explosives (HE). In the JWL EOS, the pressure $P$ is a function of relative volume $V$ and specific internal energy $E$, as follows:

$$P = A \left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega}{V} E$$

(3.3)

where $\omega$, $A$, $B$, $R_1$, and $R_2$ are empirical parameters. Here, we adopt the parameters given by Dobratz [8]. Table 1 lists the material parameters for HE and air.

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<th>Material</th>
<th>Ls-dyna material types, material property input data and EOS input data (unit: m, kg, s)</th>
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| Pentolite| *MAT_HIGH_EXPLOSIVE_BURN
|          | $\rho_0$ | $V_D$ | $P_{CJ}$ |
|          | 1700     | 7530  | 2.55E+10 |
| Pentolite| *EOS_JWL  |
|          | $A$     | $B$    | $R_1$  | $R_2$  | $\omega$ | $E_0$  | $V_0$  |
|          | 5.412E+11 | 9.371E+9 | 4.5     | 1.1     | 0.35     | 8.1E+9 | 1.0     |
| Air      | *MAT_NULL |
|          | $\rho_0$ | $P_C$ | $u$ |
|          | 1.29   | 0.0   | 0.0 |
| Air      | *EOS_LINEAR_POLYNOMIAL |
|          | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $E_0$ | $V_0$ |
|          | 0     | 0     | 0     | 0     | 0.4   | 0.4   | 0     | 2.5E+5 | 1.0 |
3.3 Gas pressure due to explosion within a fully-constraint chamber

In this case study, the setup for the explosion is similar to that in the DLV tests except that the freely-movable roof slab is now fully clamped to the sidewalls of the chamber so that the explosive is detonated with full constraint. The time history of the gas pressure is traced. The tracking period is about 100 ms (0.100 seconds). Loading density is 1 kg/m$^3$. Fig. 2 shows the quarter model.

![Quarter model for the fully-constraint explosion](image)

Figs. 3a and 3b show the shock wave propagation. Note that the shock front is similar to the geometry of the shaped charge - semispherical in upper space. At about 0.12 ms, the shock front reaches the roof boundary. Fig. 3c shows the final pressure contours with fluctuation less than 0.05 MPa, in the range of 1.458-1.537 MPa (1.5 ± 0.042 MPa).

![Shock wave propagation and gas pressure](image)

Fig. 4 shows the pressure history at two different locations marked in Fig. 2. One is right below the
roof center and another is the upper corner of the chamber. It can be seen from Fig. 4 that the extreme pressure peak occurs at the very beginning and it is followed by a train of lower pressure peaks, obviously in the early period of 10 ms. The train of pressure peaks is caused by wave reflection. In addition, the values of peak pressure at the two different locations are markedly different with the higher one occurred at the corner of the chamber due to the composite reflections. At 70 ms, both pressure curves fluctuate about the value of 1.5 MPa within a range of 0.05 MPa. If the explosive is changed to TNT (the burn model and JWL parameters can also be found in Dobratz [8]), the residual pressure is about 1.2 MPa. It is comparable to the estimation using prevailing empirical formulae: $P = 1.30m/V$ for most HE by Carlson [9]; and $P = (1.34 \pm 0.19)m/V$ by Moir [10], in which $m$ is in kg, $V$ is in m$^3$ and $P$ is in MPa. Here $m = 1$ kg and $V = 1$ m$^3$.

3.4 Launching velocity derived from blast shock pressure

In this case study, the setup for the explosion is similar to that in the DLV tests but with no chamber at all. The free top plate is left in place and subjected to underneath open-air explosion. As such, the top slab is only propelled and accelerated by the blast shock. The quarter model is shown in Fig. 5.

Fig. 6 shows the shock wave propagation. Note that the shock wave travels outwards continually. At about 0.2 ms (as can be seen from Fig. 6a), the shock front reaches and interacts with the top plate fully. Fig. 6b shows the snap shot at 0.5 ms when the shock front has propagated further outwards such that the propelling source vanishes. Instead, negative pressure is created underneath the plate. At later times, 1 and 3.5 ms (as can be seen from Figs. 6c and 6d), the pressures surrounding the plate diminishes quickly. It drops to nearly the atmosphere pressure at 3.5 ms.
Fig. 7 shows the time history of velocity and acceleration. The present ALE simulation yields a velocity curve increasing sharply from 0 to the maximum of 4.1 m/s at about 0.5 ms (corresponding to snapshot in Fig. 6b), and then decreasing gently to about 3.4 m/s. This post-peak velocity drop is caused by the negative pressure underneath as depicted in Fig. 6c. Correspondingly, Fig. 7b shows the acceleration curve, which also spikes up sharply to the maximum of about $3.19 \times 10^3$ g at about 0.2 ms (corresponding to snapshot in Fig. 6a).

To investigate the blast effect on a structure, a common alternative practice is to apply the air-blast pressures directly to the structure, which is simulated using Lagrangian formulation. In the computer code Ls-dyna [11], the air-blast pressure can be defined by a blast-load function, which is based on the empirical blast models of Kingery and Bulmash [12-13]. This simple approach neglects the air/fluid response, and the blast pressure is derived purely from the equivalent weight of TNT at the charge center. The results obtained from this simplified approach are also plotted in Fig. 7 for comparison. It yields a peak velocity of 4.3 m/s and a peak acceleration of about $2.57 \times 10^3$ g. Note that the acceleration drops to zero at about 0.5 ms which means that the active blast wave duration is about 0.5 ms. It is comparable with the results by the present ALE approach. However, it should be mentioned that the Pentolite is supposed to be 1.4 times of equivalent TNT and regarded as air blast of spherical charge in this simulation. And in the simulation, the obtained reflected pressure is based on infinite reflective surface and does not consider the pressure-relief effect caused by finite plate size. The pressure-relief can significantly reduce the magnitude of the late-time portion of the positive reflected pressure phase, resulting in a substantial decrease in the peak impulse load [14]. So the plate velocity obtained by this method will be higher than the real velocity.
3.5 Launching velocity derived from both blast and gas pressures

In this case study, the setup of the DLV tests is simulated. For clarity, the rigid steel chamber is replaced and modeled as rigid boundary conditions. Quarter model is built as shown in Fig. 8. The part details comprising the top slab, upper air space and the explosive are shown in Fig. 8b.

![DLV Test (1kg-1m2-240kg/m2)](image)

(a) Model configuration  (b) Mesh

Fig. 8 DLV test model

Fig. 9 depicts the slab launching process under the effects of both blast and gas pressure. Fig. 9a shows the blast wave front reaching the slab at about 0.12 ms. As can be seen from Fig. 9b at 0.19 ms, the blast pressure is amplified by wave reflection. At 1.9 ms (see Fig. 9c), the slab is pushed up and away from its original location, and the pressure contours expand into the outside air space. It signals gas leaking. At later times, 3.9 through 12.1 ms (see Figs. 9d-h), the slab continues to move upwards, and the average pressure in the chamber continues to drop (from about 1.5 MPa at 3.9 ms, to 0.6 MPa at 6.1 ms, to 0.35 MPa at 8.1 ms, to 0.2 MPa at 10.0 ms and finally 0.1 MPa at 12.1 ms). Note that in Fig. 9g, the pressures above and underneath the slab are the same. It signals that the launching velocity has reached its peak value. The series of snapshots reveals that the pressure exerted on the slab is at first mainly by the blast pressure, then by the blast reflection and gas pressure, and finally by the gas pressure.

![Snapshots of slab launching process](image)

(a) 0.12 ms  (b) 0.19 ms  (c) 1.9 ms  (d) 3.9 ms  (e) 6.1 ms  (f) 8.1 ms
Figs. 10a-b shows the time history of velocity and acceleration. The present ALE simulation yields a velocity curve increasing steadily from 0 to the maximum of 36.5 m/s at about 10 ms and then staying at that peak value (see Fig. 10a). However, a closer scrutiny reveals that the rising curve is not very smooth but in wavy form. It can be explained from the corresponding wavy acceleration curve shown in Fig. 10b, which have 5 obvious acceleration peaks in association with the first blast shock and the subsequent blast reflections. Acceleration peaks 1, 3, 4 and 5 correspond to the snapshots in Figs. 9b-e, respectively. Also, the acceleration drops to almost zero at about 12 ms, which corresponds to the snapshot in Fig. 9h. Acceleration peak 1 spikes up to the maximum of 3.052x10^{-2} g.

Fig. 10c shows the time history of displacement, which increases slowly in early time and then almost linearly in later time. Fig. 10d shows the time history of pressure directly underneath the slab center. It can be seen that there are also five obvious pressure peaks, which results in five peaks in the acceleration curve. Note that the pressure eventually drops to the atmosphere pressure of 0.1 MPa, different from that in fully constraint case, which has a residual pressure of 1.5 MPa.
With regard to the launching velocity, present simulation result of 36.5 m/s is comparable with the DLV field test results of 33.8 m/s [1] and also the estimation (33 m/s) by van Doormaal [3], who provided a qualitatively interpretation for the launching mechanism and developed a simple phenomenological model for quantitative estimation of the launching velocity and displacement. Results derived from van Doormaal model are also plotted in Figs. 10a and 10c for comparison. In the van Doormaal model, the initial velocity of 6 m/s is computed based on the impulse of the initial peak reflected pressure and the estimated rise time of the gas pressure is about 5ms. After this period, the gas pressure pushes the slab upwards with the initial velocity. The gas pressure will leak when the slab rises. By comparing the van Doormaal curves with the present curves directly, one may find substantial discord at a glance. However, upon disregarding the start time and translate the van Doormaal velocity curve by 0.5ms which is the decay time for the first peak in the present model, a very good agreement can be observed. In addition, the displacement curves are found in good accord after the translation.

4. Conclusions

A series of numerical simulations under variable conditions are carried out to study the effect of blast pressure and gas pressure on debris launching velocity. Results are in good agreement with available experiment data and empirical equations. It provides insight and explanations for the debris launching process which is hardly observed in the experiments. This study verifies the different effects on the resulting debris launching velocity due to the blast pressure and the gas pressure. It also shows that the gas pressure has dominant effect on the debris launching velocity. In addition, simulation results reveal that wave reflections play an important in determination of active blast pressure duration and the resulting launching velocity. In conclusion, the mechanism of internal pressure formation shall be derived from the initial blast pressure, subsequent blast wave reflections and the accumulated gas pressure. This effort would help interpret the data/observations obtained from a full simulation of a magazine structural break up and the subsequent debris dispersion due to an internal detonation.

References

Speaker’s biography

Dr. YU graduated from Northwestern Polytechnical University, China with a PhD in Solid Mechanics. He is now a research fellow of the Protective Technology Research Center (PTRC), Nanyang Technological University, Singapore. His research interest focuses on Dynamic response of Material and Structure.