A Study of Blast Phenomenon due to an Explosion of TNT Encapsulated by Steel Casing Shell: Experimental and Numerical Analyses Using LS-DYNA

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***Abstract*—The increasing threat of a blast explosion from high explosive devices, such as trinitro-toluene (TNT) encapsulated by a steel casing shell, makes the study of the blast phenomenon more important. In this paper, a study of the blast phenomenon due to TNT was studied. Both experimental and numerical analyses were done. The explosive system comprises 80 kg of TNT encapsulated by a steel casing shell, with the total weight of the device being 250 kg. Experimental results showed that the blast velocity was found to be 827 m/s, while the shrapnel velocity was 802 m/s. Numerical analysis using LS-DYNA simulated the explosion sequences in detail and predicted the maximum velocity of the shrapnel.**

***Index Terms*—blast explosion, TNT, steel casing shell, LS-DYNA**

I. Introduction

A study of blast and high energy impact on structures due to an explosion of high explosive materials such as tri-nitro-toluene (TNT) is gaining more attention to researchers worldwide owing to an increasing threat of a terrorist attack. The explosion of TNT could produce severe damage on structures, such as building and land vehicles, ship and even aircraft. A 5 psi blast overpressure will produce maximum wind speed of 163 mph that will produce collapse on most buildings and spread the fatalities. However, a 20 psi blast overpressure will produce a maximum wind speed of 502 mph, and the percentage of fatalities will approach 100% [1]. The amount of overpressure on structures due to an explosion depends on the mass of TNT, the distance between the structures, and the point where an explosion occurs [2]. For example, a 100 kg TNT explosion at a distance of 15 m will produce an overpressure of 0.27 MPa (39 psi), which will produce severe damage on the perimeters.

The effect of blast loading from a TNT explosion on structures has been a main subject of research. The effect of blast loading on buildings has been presented [3,4]. Gebbeken [3] presented his finding of blast impact on buildings and the method to increase the resistance of buildings on a landscape during blast explosion, while Verma [4] analysed the effect of blasts on building structures such as masonry. They investigated the LPG gas cylinder burst instead of a TNT explosion on the building. The development of modern vehicle technology, such as land, marine and air vehicles, requires lightweight materials and structures such as composite and sandwich structures. Giversen [5] studied the effect of blast loading on composite structures used in armoured vehicles using experimental data and numerical analysis via LS-DYNA to analyse those effects. They reported that the model was 19% lower than the experimental results. Moreover, Avachat [6] investigated the use of composite materials for blast mitigation in marine structures, while Abada et al [7] investigated the sandwich structures of steel plate and aluminium foam for the use of armoured vehicles, using finite element analysis. The analysis and modelling of the explosive containment box in aircraft has been presented by Burns [8].

Additionally, work on the blast effect on structures, particularly unidirectional fibre reinforced composites, was given by Batra and Hassan [9]. They investigated the effect of plate boundary conditions and lay-up configuration to the failure mode of composite structures due to blast loading. These researchers found that clamped edges dissipated energy nearly twice that for simply supported edges. Sriram and Vaidya [10] used LS-DYNA to investigate the effect of blasts on aluminium foam composite sandwich panels. The aluminium core failed in core failure while the face sheet failed in matrix failure. Finally, Arora et al [11] used glass-fibre reinforced polymer sandwich structures to resist blast loading of a 30 kg C4 explosive at a stand-off distance of 8–14 m. They also found that plate boundary conditions played an important role for the plate deformation and failure, as given by Ref. [9] as well.

The work done by many researchers cited above mostly focussed on the effect of the blast itself, *i.e.* loadings due to the propagation of a shockwave to a structure, whether metallic, composite or sandwich structure. However, most TNTs used were encapsulated

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by a steel casing shell. During the explosion, the steel shell will be destroyed into shrapnels that fly in every direction with high speeds. These sharpnels severely damage the surrounding area, even causing fatalities to people. Therefore, a blast study of TNT encapsulated by a steel casing should also include the sharpnels' phenomena. In this paper, a thorough study on the explosion of TNT encapsulated by a steel casing shell will be presented. Both experimental and numerical analyses using LS-DYNA analysis will be investigated, including the blast loading and sharpnel velocity after explosion.

II. Experimental Setup

A steel shell with a diameter of 325 mm, length of 823 mm and thickness of 20 mm was filled with 80 kg of TNT high explosive materials. The total weight of the system was 250 kg. There are two types of experiments. The open air explosion to determine the blast and shrapnel velocities after the explosion and the underground explosion to measure the shape and weight of the shrapnel.

A. Open Air Explosion

Fig. 1 shows the experimental setup. The steel-TNT was put on the ground, and the TNT was detonated from a distance. In several distances from the explosion point, a 3 mm steel plate was installed to capture the shrapnel and to determine the effect of the steel-TNT explosion on each distance.

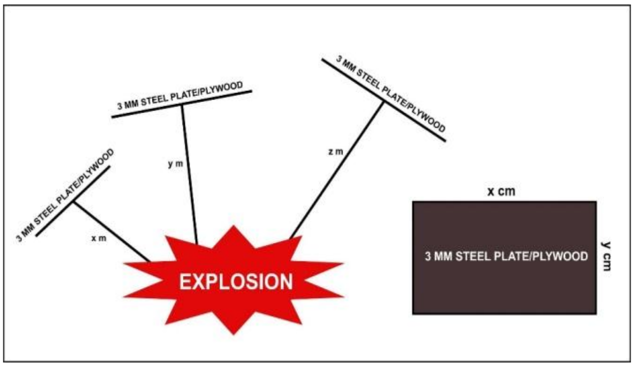


Figure 1. Experimental setup for the open air explosion

The explosion was recorded using high speed video camera. Fig. 2 shows the explosion for the open air type, while Fig. 3 shows the calculated speed of the shrapnel and the shockwave. Fig 3 shows that the shrapnel speed was recorded at 802 m/s while the shockwave speed was 827 m/s.

Fig. 3 gives evidence that the velocity of the shockwave after explosion is higher than the shrapnel velocity. Therefore, the structures due to the high explosion will experience the blast loading first, before they experience the high velocity impact of the sharpnel. Notably, this finding is important to analyse further the effect of blast explosion on structures.

Figure 2. The blast during open air explosion

(a)

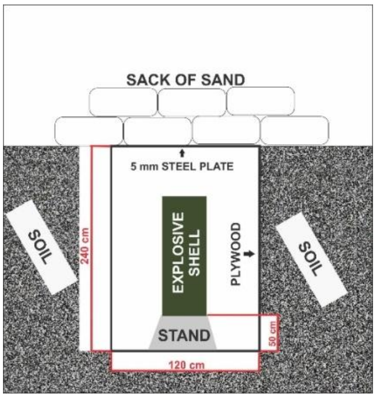
(b)

Figure 3. Sharpnel velocity (a) and shockwave velocity (b) after explosion

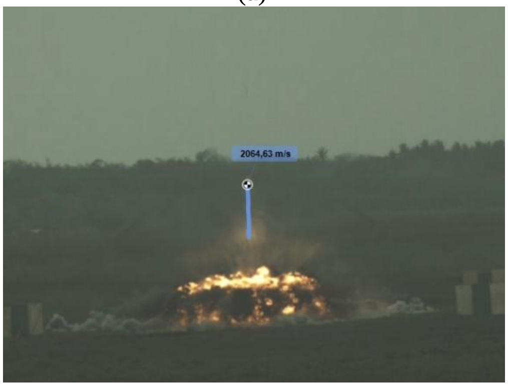
B. Underground Explosion

The second experiment is underground explosion. In this case, the TNT steel shell was buried under the ground in 240 cm deep. The underground explosion experiment was used to collect the steel sharpnels produced after the explosion. Fig. 4 shows the experimental setup and also the image after the explosion over ground.

After the explosion, the sharpnel was collected and measured. Fig. 5 shows the size distribution of the sharpnel collected after the explosion.



(a)



(b)

Figure 4. (a) Experimental setup and (b) after explosion of an underground explosion experiment

Figure 5. The sharpnels' sizes after explosion

The weight distribution of the shrapnels is given in Fig 6. The x-axis is the shrapnel weight and the y-axis is the number of shrapnels. This figure shows that the maximum number of shrapnels after an explosion has a weight of 11–30 g. These data are important in analysing the effect of shrapnels on structures during the blast explosion.

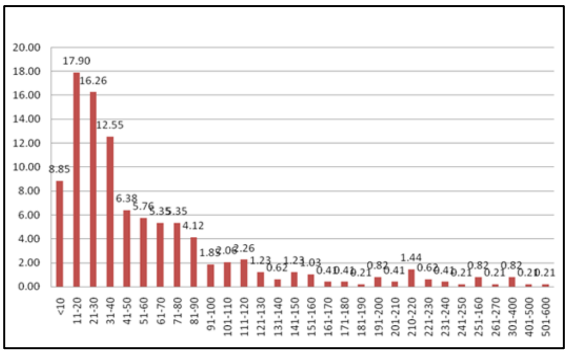


Figure 6. The weight distribution of the sharpnels

III. Numerical Analysis

The numerical analysis extensively used LS-DYNA. The steel casing shell was modelled in a shell element, and the steel shell element material model used the Modified Johnson-Cook steel material model. The model is able to simulate the behaviour of the steel shell under blast explosive loading. The model considers the effect of strain hardening, coupled strain rate and temperature on flow stress which are mutually dependent.

The Johnson-Cook model used in the analysis is given in Eq. 1, Ref. [12]:

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_1 ln\varepsilon^*)exp[(\lambda_1 + \lambda_2 ln\varepsilon^*)(T - T_r)], \quad (1)$$

where

σ: equivalent flow stress

ε: equivalent plastic strain

T: absolute temperature

$T_{r:}$ reference temperature

$\varepsilon^* = \varepsilon/\varepsilon_o$: dimensionless strain rate

$A_1, B_1, B_2, C_1, \lambda_1, \lambda_2$: material constants

For the TNT explosive materials, a smoothed particle hydrodynamics (SPH) element was used. SPH is a meshless numerical method that was used to simulate extreme deformation problems by the defining N-nodes particle integration scheme. This method discretizes the physical continuum into unconnected particles that have the physical properties. The field function of SPH, for example, velocity, temperature, mass and pressure, of a discrete particle is influenced from the field function of all neighbouring particles weighted by a smoothing function. The smoothing kernel function considers the effect of surrounding particles which is defined in a certain radius length, called smoothing length, Ref. [13].

The kernel function (W) with the smoothing kernel called cubic B-spline is the most common variable used by the SPH community and in LS-DYNA. The cubic B-spline that was developed by Monaghan et al [14] is used in the present analysis to calculate the intensity of interaction between neighbouring particles in a three-dimensional SPH model. The B-spline model is given in Eq. 2:

$$W_{ij} = \frac{1}{\pi h^3}\begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 \; if \; 0 \leq q \leq 1 \\ \frac{1}{4}(2-q)^3 \; if \; 1 \leq q \leq 2 \\ 0 \; if \; 2 < q \end{cases}, \quad (2)$$

where q=r/h

r is the distance between two neighbouring particles, and h is the smoothing length.

The particle approximation of a function in SPH is given by Eq. 3:

$$f(x_i) \approx \int f(x_j)\, W(x_{ij}, h) dx \quad (3)$$

In this numerical simulation, the SPH element is applied into the TNT material model MAT_HIGH_EXPLOSIVE_BURN by using LS-DYNA. At initial setup, physical and geometrical properties are the most important properties to be setup. The physical properties such as density and mass are defined in the PART card and in the ELEMENT_SPH. In the case of geometry, where the particles are initially placed, the more uniform distance of every particle is better. The calculation step cycle in detail is given in [15].

The finite element model of the TNT encapsulated by a steel casing shell is given in Fig. 7. This figure shows that the steel shell was modelled using a shell element of the Johnson-Cook type, while the TNT was modelled using the SPH element. The SPH element was placed inside the steel shell element.

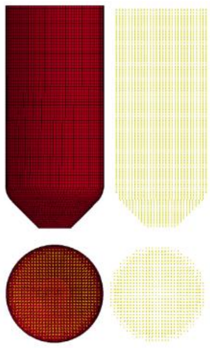


Figure 7. Finite element model of the steel-TNT device. Shell element of the steel *(left)* and SPH element of the TNT (*right*)

The results of the LS-DYNA analysis are given in Figure 8. This figure shows the time sequences of a blast explosion of steel-TNT from 0 sec to 0.0008 sec. Additionally, this figure shows that the blast occurred in a very short time.

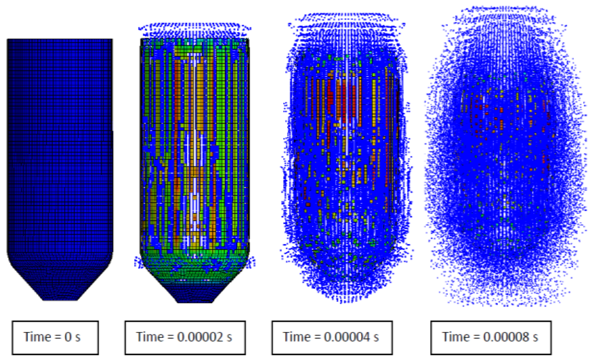


Figure 8. Explosion sequences of the steel-TNT blast explosion

Another thing that is important is the speed of the shrapnel. The shrapnel velocity can be calculated in LS-DYNA and it was found that the maximum velocity was 1266 m/s, compared to the average velocity of 802 m/s during the experiments, as shown in Fig 3.

To verify the numerical analysis, the energy during the explosion was calculated. It was that the hourglass energy, as well as damping energy was very small, i.e. approaching zero values. Therefore, the numerical analysis was stable.

IV. Conclusion

A blast explosion of 80 kg TNT encapsulated by a steel casing shell with a total weight of 250 kg was studied. Both open air and underground explosions were presented. The experimental study showed that the blast velocity due to a shockwave is higher than the shrapnel velocity. The blast velocity was found at 827 m/s, while the shrapnel velocity was at 802 m/s. The weight distribution of the shrapnel after an explosion was calculated, and results showed that the maximum amount of shrapnel was in the range of 11–30 g. The numerical analysis was done using LS-DYNA. The steel casing was modelled using a shell element with a Modified Johnson-Cook material model, while the TNT was modelled using SPH elements. The numerical analysis was able to determine details of explosion sequences and the analysis calculated that the maximum velocity of the shrapnel was 1266 m/s. Notably, the numerical analysis gives the maximum velocity, while the experimental analysis gives the average velocity.

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