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PREDICTED AND EXPERIMENTAL RESULTS OF SHAPED CHARGE PENETRATION WITH LINERS OF MEASURED WALL THICKNESS VARIATION

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Penetration trials were conducted with shaped charges of a specific design. The copper liners used in the high precision charges were within specification in terms of roundness, but had known wall thickness variations in planes perpendicular to the symmetry axis. The penetration results obtained with the charges are compared with the predictions of a previously reported statistical model of jet penetration, which was adapted to cater for the possibility of a jet which has a radial deviation from the warhead symmetry axis due to a specific quantifiable warhead asymmetry. The radial velocity of the jet, which is used as an input in the model, was deduced from orthogonal streak measurements, as well as from numerical/analytical simulations.

INTRODUCTION

The importance of component symmetry for shaped charge warheads is well appreciated by those who have had prolonged exposure in this field. A survey of some of the historical experimental research and identification of the more important symmetry parameters which affect the penetrative performance of a shaped charge, can be found in [1]. The effect of wall thickness variation of the shaped charge liner on performance, in particular, has been researced to various degrees [2,3,4]. It was, however, in the past quite difficult to experimentally isolate the effect of a specific symmetry parameter on performance. This was largely a consequence of aspects such as the inherent quality of the explosive filling, liner metallurgy and charge confinement. Recent advances in shaped charge technology have improved the situation considerably.

The prediction of shaped charge penetration performance is a well researched field. Most predictive models are of an analytical nature and a good overview of the earlier models can be found in [5]. Most models address a jet of which all the jet segments are initially aligned with the warhead symmetry axis, and then compensate for jet imperfections by introducing parameters such as the “cut-off velocity” [6]. This “cut-off” is associated with the early collision of jet particles with the crater wall due to the radial “drift” of the particles [6,7], a direct consequence of deviations in component or detonation symmetry.

A few penetration models directly account for the radial velocity of the jet [7,8,9,13]. Understandably, no models exist which account for additional disruptive phenomena (increasing the jet drift or tumbling rate) occurring inside a target. The mechanisms inside the target which may add to the "radial drift" of the particles are complex and not easily quantifiable. For this reason a statistical model was formulated previously [10] that is based on a stochastic (normally distributed) radial velocity component to account for both inherent small and random shaped charge asymmetries and/or in situ disturbances originating inside the target.

In this paper the results of penetration tests of precision shaped charges, but with liners of measured wall thickness variation, are reported. Furthermore, the statistical model [10] is adapted to include both the stochastic radial velocity component as well as an offset radial velocity component which is associated with a specific bulk asymmetry.

EXPERIMENTAL

The liner of the shaped charge used in this study was of the variable-angle variable-thickness type and explosive pressed plastic bonded explosive was used for the charge. The charge diameter was greater than 100 mm and the jet tip velocity of the charge was 9.7 mm/µs. The average scaled break-up time of the jet was greater than 2 µs/mm.

The target in the test setup consisted of stacked (50 mm thick) EN24T steel (260-320 BHN) billets of 250 mm diameter. The stand-off was 3.5 caliber. The available liners had a range of liner wall thickness variation which was approximately 0.4% to 7.5% of the liner (apex) thickness. The wall thickness variation was not uniform throughout the liners but it was consistent with the maximum variation at the liner apex and no variation at the liner base. Only the maximum variation is quoted in this paper. A total of 17 firings was conducted. All penetrations are normalised to the performance of the highest penetration (attained with a liner with a wall thickness variation of 0.4% of the liner thickness).

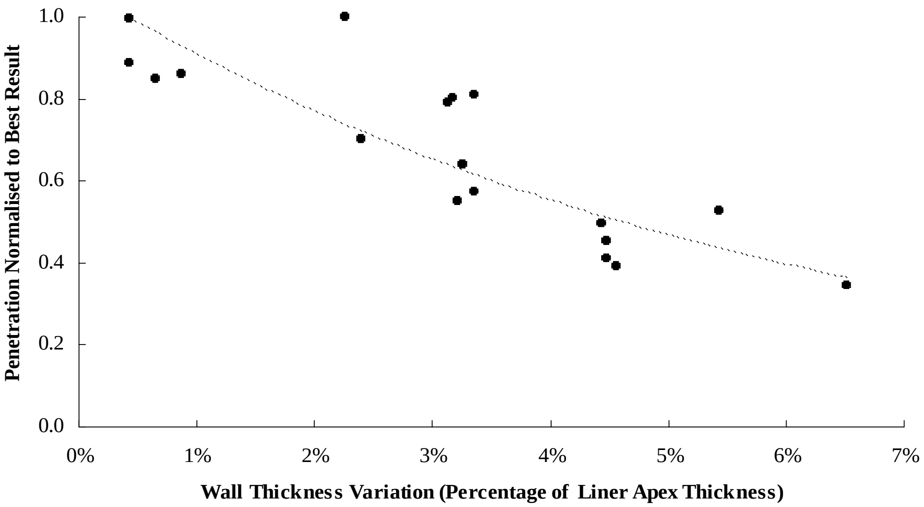

Figure 1. Normalised penetration results.

The results are shown in Figure 1. Since it is a fair assumption that the trend should be exponential rather than linear, an exponential curve was fitted through the experimental points as a guide.

ESTIMATION OF THE RADIAL VELOCITY

The finite difference code Autodyn-2DTM was used to calculate velocities of the liner elements with marginally different thicknesses at a fixed axial position. The numerical velocity estimation enabled the calculation of momentum differences of symmetrically collapsing mass elements of specific thickness, similar to [4]. The assumption of collapse symmetry leads to a lower limit estimate of the particle radial velocity resulting from the collision of elements of different momentum. Specific examples of the estimates of the radial velocities of jet segments (particles) resulting from liner wall thickness variations used in the present case study are shown in Table 1.

Table 1 : Estimated radial velocities

Wall Thickness Variation (%)	**Radial Velocity (m/s)**
0.4	5
1	9
2	17
4	32
6	47

MODELLING

The basis of the statistical model [10] is that the *expected* penetration is defined by the relation:

$$X = \sum_{i}^{n} P_i l_i \gamma \tag{1}$$

where P_i is the probability that the segment (or particle) i will impact the bottom of the crater, l_i is the length of the segment (or particle) when it reaches the bottom of the crater and γ the square-root of the density ratio of the jet and the target. P_i was previously [10] calculated from assuming a normal distribution around a mean radial velocity and imposing a standard deviation. This approach did not cater for the possibility, as in the present case, of a radial velocity contribution from a deterministic effect, such as a known asymmetry, which is divorced from the inherent statistical component.

In order to adapt the statistical model to include the radial velocity contribution from a known asymmetry, a more direct approach is taken in the calculation of the probability P_i. Consider the impact of particle on a centroid impact point (x_0, y_0) as in Figure 2, such as for a hypothetical jet segment moving through a cross section of the target. We assume a bivariate normal distribution of the particles, but then impose symmetry around the average impact point. The distribution is fully characterised by the standard deviation representing the inherent radial dispersion in the jet. The jet crater is represented by a circle of radius R (the smallest crater radius at the time) at the origin caused by the previous jet element. The distance from the origin to the impact point (x_0, y_0) represents the radial drift due to a known asymmetry.

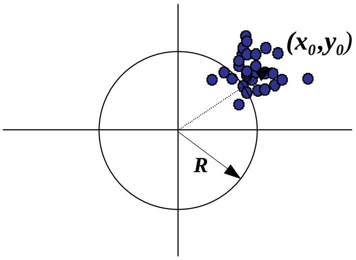

Figure 2: Schematic representation of particles superimposed on the crater.

Since the distribution is assumed to be symmetric, the axis system can always be rotated such that $y_0=0$. The dispersion of the particles is therefore given by:

$$\varphi(x,y)=\frac{1}{2\pi\sigma^2}e^{-\frac{1}{2\sigma^2}[(x-x_0)^2+y^2]} \tag{2}$$

Transforming equation (2) to polar coordinates yields:

$$\varphi(r,\theta)=\frac{\alpha^2}{\pi}e^{-\alpha^2[r^2-2x_0 r\cos\theta+x_0^2]} \tag{3}$$

where

$$\alpha=\frac{1}{\sigma\sqrt{2}} \tag{4}$$

The probability of finding a particle in the circle with radius R is then:

$$P(r,\theta)=\int_0^{2\pi}\int_0^{R}\left[\frac{\alpha^2}{\pi}e^{-\alpha^2[r^2-2x_0 r\cos\theta+x_0^2]}\right]r\ dr\ d\theta \tag{5}$$

The integral in (5) is solvable analytically by means of the introduction of a Bessel-function and a further series expansion [11], but it was preferred to compute the integral numerically for each jet segment (particle). In the computation the radial velocity distribution of each jet velocity segment is characterised by the input of its standard deviation, which is then transformed to a radial standard deviation at time *t*. Similarly the off-set (x_o) is calculated by using the radial velocity of the known asymmetry and the time *t*.

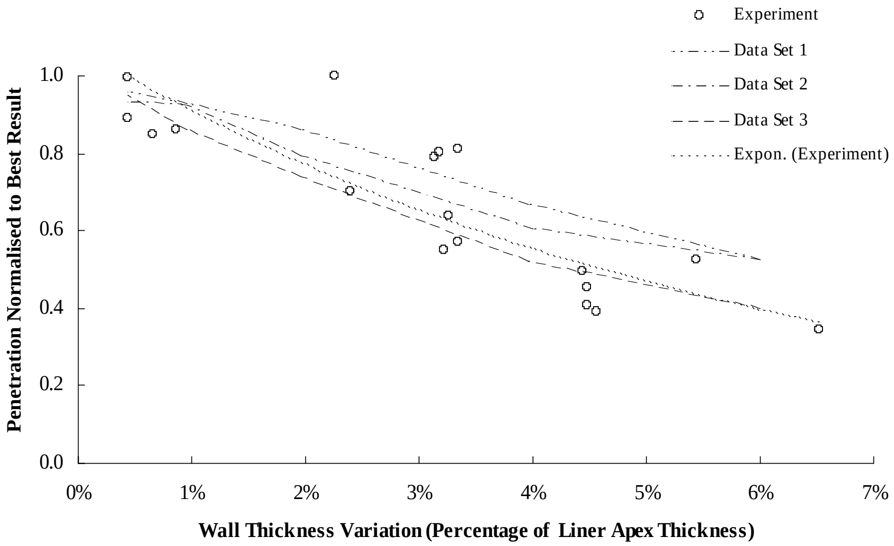

Figure 3. Model predictions compared with the experiment.

DISCUSSION

Radial jet velocities can be deduced from orthogonal synchro-streak (OSST) records [12] or orthogonal flash-X-ray (FX) records of the jet [4]. In these experiments the radial displacement of the particles relative to some datum line is measured in two directions. Typical values that are given for shaped charges of various degrees of precision vary between 0 and 100 m/s [4,6,9]. However, estimates from local experiments (in air) with high precision charges yield values less than 30 m/s and Chi [13] uses a maximum of 40 m/s to model the penetration of a 65 mm diameter precision shaped charge.

In Figure 3 the model predictions with the adapted statistical model are compared to the experimental points (exponential fit) defined in Figure 1. The radial velocity data sets used in the predictions are given in Tables 2 and 3.

Table 2: Radial velocity distribution

Data Set 1		Data Set 2		Data Set 3	
Jet Velocity (mm/µs)	**Std. Dev. (m/s)**	**Jet Velocity (mm/µs)**	**Std. Dev. (m/s)**	**Jet Velocity (mm/µs)**	**Std. Dev. (m/s)**
9-8	5	9-8	15	9-8	15
7-5	10	7-5	15	7-5	15
5-4	15	5-4	15	5-4	15
4-3	20	4-3	15	4-3	15
3-2	25	3-2	15	3-2	15

Table 3: Offset radial velocities

Data Set 1		**Data Set 2**		**Data Set 3**	
Thickness Variation	**Offset (m/s)**	**Thickness Variation**	**Offset (m/s)**	**Thickness Variation**	**Offset (m/s)**
0.4 %	5	0.4 %	5	0.4 %	5
1 %	9	1 %	9	1 %	14
2 %	17	2 %	17	2 %	25
4 %	32	4 %	32	4 %	48
6 %	47	6 %	47	6 %	70

The radial velocity distribution data in the first data set used in Figure 3 was previously found to predict the stand-off behavior of two different shaped charge warheads reasonably well [10]. The difference here is that the values represent the standard deviation and not the mean of the normal distribution. In Data Sets 2 and 3 the standard deviation of the distribution was kept constant throughout the jet. The radial velocity off-set values were obtained from Table 1 except for Data Set 3 where the values were increased by 50% to compensate for the fact that these were lower limit values.

Figure 3 shows that good correlation is obtained with the adapted statistical model and the trend in the experimental results. The predictions with Data Set 1 and 2 are somewhat higher than the exponential fit, but this could also be due to the lower limit estimates of the offset radial velocity and the possibility that increased tumbling of particles or disturbances inside the crater may occur with jets which have an offset radial velocity from a deterministic asymmetry. A major improvement in the statistical model is the specification of a single parameter for the stochastic radial velocity distribution. The extreme sensitivity of the model (in the absence of a radial velocity offset) to the two-parameter inputs observed previously [10] has been alleviated.

CONCLUSION

The penetration performance of a shaped charge with liners with varying wall thickness variation was characterised experimentally at a fixed stand-off. The output of the statistical model which was adapted to include both the radial velocity distribution typical of the shaped charge, as well as a known radial velocity offset (from an asymmetry) correlated acceptably with the experimental values.

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