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# BEHIND ARMOUR DEBRIS ANALYSIS METHOD

**Ms. Alta Karpenko[1], Mr. Karl Pfister[1]**

[1]*Armatec Survivability Corp.*
*6-120 Falcon St, London, ON N6A2K3 Canada*

Behind armour debris analysis is typically performed using witness pack analysis, flash radiography or a combination of the two methodologies.

Flash radiography uses timed x-rays to obtain images of the jet and debris field. These images can then be used to calculate the speed of the jet and debris field and, if the x-ray has a sufficient resolution, the size of the projectile. Witness packs record the spall pattern and collect fragments.

Typical methods of analysis involve digitizing the witness pack and using a software package to resolve the perforations. The software package can estimate the weight of the fragment and measure the position of the hole. This system is expensive and the results still have an inherent error margin.

This analysis method provides an inexpensive low tech means of obtaining reliable results.

This analysis method uses witness panels to record the spall pattern and an effected area is generated through locating and counting the resultant penetrations. Unlike traditional analysis methods, this method does not assume a circular area when calculating spall energy density. Flash radiography is used to calculate the speeds of the jet and debris field. These speeds are then used to calculate the energy of the spall fragments and the resulting energy density.

## INTRODUCTION

This paper outlines an assessment tool that intends to define an analysis procedure for behind armor effects on high hardness steel under the effects of shape charge penetration.

For assessment of vulnerability, a characterization of the behind armor effects has to be defined. The effects are described by a number of parameters. Most commonly used is the spall cone angle, accompanied by the kinetic energy of the spall fragments and their distribution pattern.

For a comparison of different protection systems, a detailed analysis of behind armor effects is needed to enable the assessment of the vulnerability of the system. The test itself has a number of variables: the warhead performance, the test set-up, the armor and the effects of the fragmentation. In order to characterize this highly dynamic system, the data is statistically analyzed to remove the random effects. For a comparison of the system vulnerability, a group of parameters has to be compared. A single value like cone angle or remaining kinetic energy alone does not represent the whole picture.

To gather the maximum amount of data during a test, the set-up includes witness block stack-ups, as well as multi-head flash x-ray photography to enable a recording of the history of events and a more thorough analysis of the static witness panel data.

Past work in this field completed by Verolme, Szymczak and Broos [5] and Szymczak, van Bree and Lans [4] detailed the use of flash x-ray and metallic witness packs for the analysis of behind armor debris but did not evaluate the performance of protection systems. Studies completed by Arnold and Paul [3] and Arnold and Rottenkolber [2] looked at the effect of polyethylene liners and demonstrated vulnerability simulations for armored vehicles but assumed a circular fragment distribution.

## TEST SETUP

The witness block is a stack-up of plates positioned under the target to allow the spall pattern to be documented. The projectiles created by the spall create holes and dents in the witness plates. These marks can then be analyzed to determine the size of the spall cone as well as the energy level of the projectiles. The witness block stack up is based on STANAG 4190 [1] specifications, and contains layers of aluminum and polystyrene foam, backed with a 1.5mm steel sheet.

## CLASSIFICATION OF FULL AND PARTIAL PENETRATIONS

For the purpose of this analysis, a hole is defined as an area of complete penetration. These were identified by placing a light behind the witness panel, and areas of the panel where the light could be seen, were considered holes regardless of the diameter. In this analysis, partial penetrations or dents are classified as deformations in the panel which can be felt on the back side of the panel.

## WITNESS PLATE DATA COLLECTION

A template is made up on acetate so that the distance from the center of the blast to the dents and holes created by the spall could be easily measured. The template is divided into wedge segments of 20 degrees each and radii in 20 mm increments.

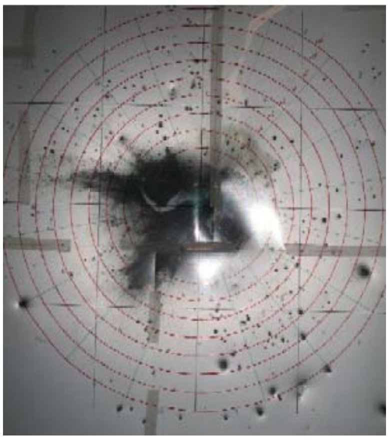

**Figure 1: Template on Witness Plate**

The number of holes in each section of the template are counted and tallied in a spreadsheet. In addition to the number of holes that occur within each radius, it is also important to note the number of marks outside the largest radius in order to determine the accuracy of the average. If too many marks are outside the largest radius then the size of the template needs to be enlarged to enclose these marks. Ideally, the template should encompass over 90% of the deformations on the panel.

## WITNESS PLATE DATA PROCESSING

### Determining Spall Cone Angle

Traditionally, spall cone angle is determined using the hole furthest from the main penetration to determine a maximum radius. The spall cone is then projected from the target to this maximum radius, and the angle determined. Because the steel target is not homogenous and the nature of the projectile is highly dynamic, the distribution of the spall fragments is random. This randomness means that the hole that occurs at the farthest radius from the center of the penetration could be an aberration and not indicative of the spall pattern. In order to eliminate this inaccuracy, the frequency which holes occur in each template section is graphed, an example of which is shown in Figure 2.

If for example, the fragment with the furthest radius occurred in segment 12, the segment with the lowest frequency of holes, it is likely that is a random occurrence and not part of the typical spall pattern.

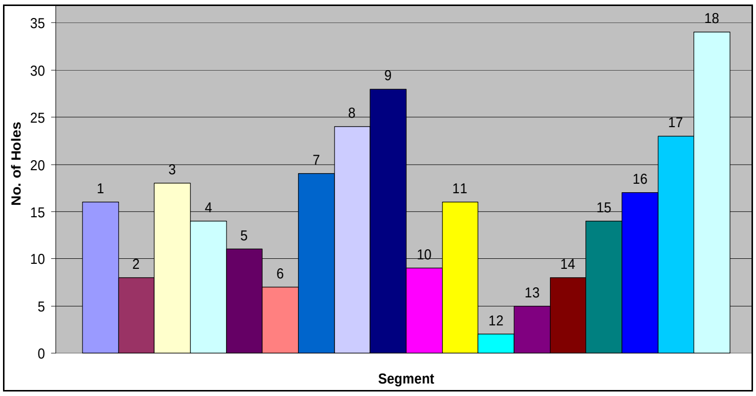

**Figure 2: Template Section Distribution**

The five segments containing the highest frequency of holes are evaluated to determine the maximum radius in each segment. These distances are averaged to find the average maximum radius. The average maximum radius is then used to calculate the spall cone angle (F) where r is the average maximum radius, h is the height from the target to the witness block.

$$\Phi = 2\tan^{-1}\left(\frac{\bar{r}}{h}\right) \qquad [1]$$

## Determining Spall Pattern Shape and Area

The spall pattern will not always be circular, it has the possibility to be elliptical or cross shaped depending on the direction that the jet penetrates the target and also the material that the target consists of.

The segment which holds the maximum number of holes for each radius is determined and shown on the template in Figure 4.

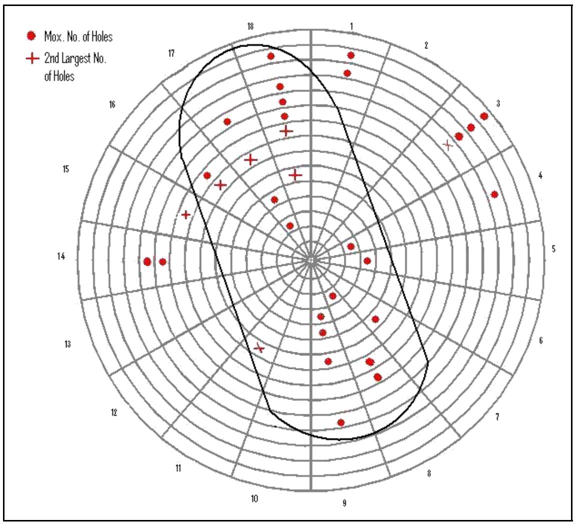

**Figure 3: Spall Pattern**

Having determined the shape of the spall pattern the area can be determined. In this example the pattern is elliptical, the radii are measured on the template and the area of the pattern is then calculated. This area can then be used to determine the energy density of the spall cone.

## WITNESS PLATE DATA INTERPRETATION

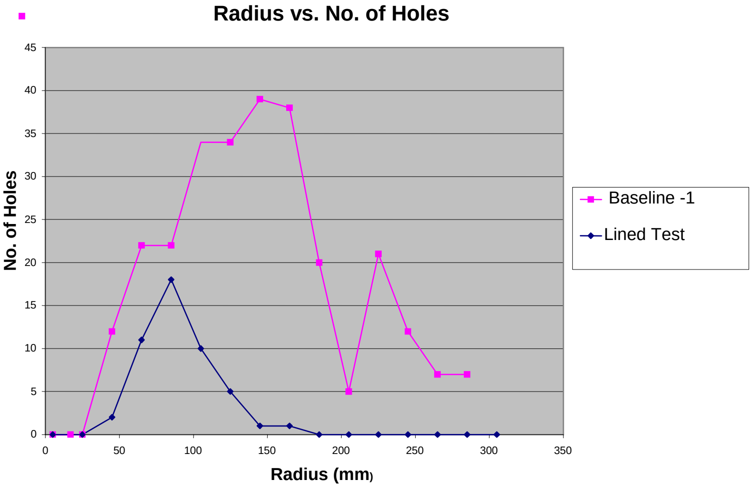

**Figure 4: Comparison of Number of Holes per Radius**

Figure 5 compares the number of holes in the first witness panel of the baseline test and a spall liner test. A graph such as this will show the difference in patterns between baseline tests and the performance of various protection systems.

The number of holes and locations are logged for each aluminum plate in the witness pack. By tabulating the number of witness plates that have been penetrated, a qualitative view of the energy level of the fragments can be seen.

Holes and dents can occur on dividing lines between radii or segments. Generally, the mark should be counted in the section in which the majority of it lies. The effect of this is minimal since the majority of the holes lie distinctly within a section of the template. It is difficult to determine where the main penetration occurs in order to center the template on the witness panel. Because of this, the template is not placed in exactly the same location on every panel in the witness pack. Since the template is designed so that the sections are large enough that a small variation (±10mm, ±10deg) in locating the template on each panel will not greatly affect the results. Because of the jagged edges formed by the main penetration it is difficult to determine where the spall pattern ends and the area of main penetration begins. Generally, this transition is marked by petalling. The main calculations are done using maximum radii; therefore variations in the inner radii would not greatly affect the results.

## FLASH X-RAY DATA COLLECTION

Flash radiography was used to gather further data from the test. Flash x-ray heads were used to take images of the jet penetrating the target and the resulting debris cloud. The x-rays are examined to determine the velocity of the jet and the debris cloud as well as the spall cone angle.

The spall cone angle can be directly measured off of the x-ray. The spall cone angle is measured as a line tangent to the edge of the cloud at the base of the target. This measured quantity can be compared to the spall cone angle calculated from the witness plate data in order to determine the accuracy of the calculated quantity and statistical analysis method.

A fiduciary line is used as a reference for taking measurements. The distance from the tip of the jet to the fiduciary in the images is measured and recorded. As well, the size and shape of the debris cloud is estimated from the fragments shown in the x-ray. The distance from the tip of the debris cloud to the fiduciary is measured in the images where the jet has penetrated the target.

## FLASH X-RAY DATA PROCESSING

The speed of the debris cloud is calculated using a spreadsheet that uses measurements from the test set up to determine a magnification factor of the image that can then be used to covert the measured values to actual values. The velocity of the debris cloud is then calculated using the distance and time. It is important to note that this is the average speed of the debris cloud and not the speed of individual particles with in it, which will vary. The speed of the jet is calculated in a similar manner.

### Determining Energy Density

The kinetic energy of a particle is given by Equation 2. The velocity of the particles is estimated using x-ray data, and the mass is estimated by collecting fragments and weighing them.

$$T = \frac{1}{2}mv^2 \qquad [2]$$

In this test set-up the polystyrene foam that is in the witness packs collects some fragments as they become embedded in them. By collecting these fragments from the foam and weighing them an average weight of the fragment can be determined. Energy density is calculated by determining the total energy of the cloud and dividing it by the area of the spall pattern. Where T is the kinetic energy, n is the number of penetrations and A is the area of the spall pattern.

$$\rho_E = \frac{Tn}{A} \qquad [3$$

## FLASH X-RAY DATA INTERPETATION

The effectiveness of the liner is shown in a reduction of the fragment velocity, reduction of the spall cone angle and spall energy density. By tabulating the results of jet velocity, debris velocity, spall energy, energy density and spall cone angle for various protection solutions, the performance of a system can easily be compared.

The flash x-ray results are subjected to three main error issues. The debris cloud is often not clearly defined leading to an error in the measurement of the spall cone and the location of the debris cloud tip. There are measurement errors inherent in the equipment used to measure the x-ray images, distance between x-ray heads and weighing the fragments. These errors should be minimized through the correct selection of measuring equipments. Errors in calculated quantities are based upon standard methods of error propagation.

## COMPARING WITNESS PLATE AND X-RAY RESULTS

The spall cone angle is measured directly from the x-ray image and is subjected to errors in both measurement and interpretation of the debris cloud. The spall cone angle that is calculated from the witness plate data is done so using a variety of average values and is thus subjected to some inaccuracies as well. The two values should be compared to evaluate the accuracy of the results.

## SUMMARY OF ANALYSIS PROCEDURE

This analysis procedure uses witness pack and flash radiography data to characterize the vulnerability criteria of various spall liners. The main criteria chosen to characterize the efficiency of the spall liners are spall cone angle, spall area and energy density.

The witness packs are analyzed using a statistical analysis of the full and partial penetrations created by the behind armor debris. As well, the witness pack is used to collect fragments that are then weighed in order to quantify the energy of the debris. The area of the spall pattern is (determined from the actual pattern formed on the witness plate and not a projected area based on spall cone in order to better represent the area which would be vulnerable to spall and provide additional accuracy in the calculation of energy density.

The flash radiography data is collected in the form of measurements directly off the x-ray images. The calculated velocities are used to calculate the kinetic energy of the fragments. The spall cone angle can also be measured directly off the x-ray.

Reducing a complex system such as this one down to a small set of variables and characteristics can lead to inaccuracies. However these are minimized through the statistical analysis performed on the witness panels to reduce the likelihood of aberrations skewing the results.

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